White Paper on Thermal Remediation Technologies for Treatment of Chlorinated Solvents

Santa Susana Field Laboratory
Simi Valley, California

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Section 1
Introduction

CDM Federal Programs (CDM Smith) has prepared this *White Paper on In Situ Thermal Remediation (ISTR) Technologies for Treatment of Chlorinated Solvents at the Santa Susana Field Laboratory (SSFL)* (referred herein as the Site) located in eastern Ventura County, California. This document was prepared for the United States (U.S.) Department of Energy (DOE) under Contract Number DE-EM0001128, pursuant to the June 2009 Treatability Study Work Plans Santa Susana Field Laboratory Ventura County, California (MWH, 2009a) and an email approval from Roger Paulson [Department of Toxic Substances Control (DTSC)] to John Jones (DOE) dated May 4, 2015. During discussions with DTSC staff regarding the implementation of the thermal bedrock treatability study, both DOE and DTSC staff agreed that a laboratory experiment heating up rock cores may not provide adequate data to assess the applicability for ISTR at SSFL. Both parties agreed that the first step should be determining whether ISTR has ever been applied to bedrock conditions similar to that found at SSFL and whether those attempts were successful in the removal of volatile organic compounds (VOC) mass from subsurface bedrock.

ISTR has been identified as a potentially applicable remedy to address mass removal of chlorinated VOCs, the primary contaminants of concern (COCs) in groundwater at the Site, where the source of contamination is less than 100 feet below ground surface (bgs). Although, the evaluation focuses on the application of thermal treatment in two Areas of the Site - Areas II and IV. There are potential candidate sites in Areas I and III (e.g., Environmental Chemistry Lab in Area III and Instrument and Equipment Laboratories in Area I) with shallow bedrock contamination (less than 100 feet bgs) where ISTR could be considered to remove some contaminant mass (partial source removal), but those locations will require further assessment on the cost-effectiveness and applicability of ISTR compared with other technologies (e.g., soil vapor extraction). That assessment will be performed in the Corrective Measures Studies (CMS).

Like many other *in situ* remediation techniques, the applicability of various types of ISTR is highly site-specific. Site lithology and hydrogeology as well as contaminant type, extent, concentration, and distribution can individually and collectively affect the feasibility and effectiveness of ISTR. In addition, because there are a variety of potentially applicable technology options for ISTR technologies, each of which has seen recent technological advances, the state-of-the-practice of ISTR is summarized herein to evaluate its applicability for the Site. Presented below are the objectives of this white paper and an outline of the ISTR evaluation.

1.1 Objectives

The objective of this white paper is to present information that will support the eventual evaluation of ISTR in the upcoming CMS to be prepared separately by DOE, NASA, and Boeing for their areas of responsibilities. Within the CMS, the ability of ISTR to meet remedial objectives in selected areas of groundwater contamination at the SSFL Site will be addressed. The ultimate remedial objectives for the Site are chlorinated solvent mass removal to a level that meets

applicable state and federal risk-based groundwater standards. The ISTR evaluation consists of a comprehensive literature review of any application of ISTR to remove VOCs from bedrock sites.

This white paper is not intended to be a comprehensive review of all reported ISTR applications, and it does not provide details regarding how ISTR systems are constructed and operated. Rather, a summary of the primary types of ISTR as well as an evaluation of the effectiveness of ISTR in reducing chlorinated VOC contamination in bedrock are provided.

1.2 Paper Organization

The white paper is organized into the following sections:

Section 1, Introduction, describes the objectives and organization of the white paper.

Section 2, Summary of Site Conditions, presents Site geology, hydrogeology, and extent of groundwater contamination. In addition, key Site features and their relevancy on thermal technology considerations is presented.

Section 3, Thermal Treatment Technologies: General Concepts & Technology Screening and Evaluation, provides a general description of the fundamentals of the various ISTR technologies and how they are implemented. A brief discussion of the technologies that may be appropriate and warrant further consideration for Site-specific application is also provided herein.

Section 4, Site-Specific Discussion of Thermal Treatment Technologies, presents the conceptual description of commercially-available thermal remediation technologies, factors affecting their selection, and other considerations in technology implementation. In addition, the most promising techniques for implementation at the Site are discussed.

Section 5, Case Studies, highlights several specific examples of full-scale implementation of thermal remediation that are most relevant to the Site.

Section 6, Cost Estimation, presents preliminary, rough-order-of-magnitude cost estimates associated with the design, implementation, monitoring, and operations and maintenance (O&M) of the most promising thermal technologies identified in this study.

Section 7, Conclusions, provides conclusions of the ISTR evaluation for its potential application as a groundwater remedy for the Site.

Section 8, References, provides a list of documents used as references throughout this paper.

Appendix A, Literature Database, provides details on the various sources of case studies and project examples that were reviewed during development of this paper. In addition, publicly available documents and reports are provided.

Section 2

Summary of Site Conditions

Established in 1947, the SSFL encompasses an area of approximately 2,850 acres in Simi Hills, Ventura County, California. A variety of industrial activities were historically conducted at the SSFL, including rocket engine testing, research and development of fuels and propellants, nuclear power, and laser research. The SSFL is divided into four administrative areas (Area I, Area II, Area III, and Area IV) and two buffer zones (**Figure 1**). Because trichloroethene (TCE) impacts exist throughout the Site, this section provides a summary of the key environmental features of the Site, as well as specific details of Area II (represented by the TCE plume at the Alfa/Bravo Area of Impacted Groundwater [AIG]) and in Area IV (represented by the shallow bedrock at the Former Sodium Disposal Facility [FSDF] impacted by TCE) (**Figure 1**). The Alfa/Bravo presentation is also a surrogate for Area I groundwater contamination issues. And Area III geologically shares conditions with Areas II and IV that additional discussions of the subsurface conditions are not warranted. Environmental features including site geology, hydrogeology, and extent of groundwater contamination in the vadose zone and in bedrock are all relevant to the evaluation of appropriate thermal technologies considerations for use at SSFL.

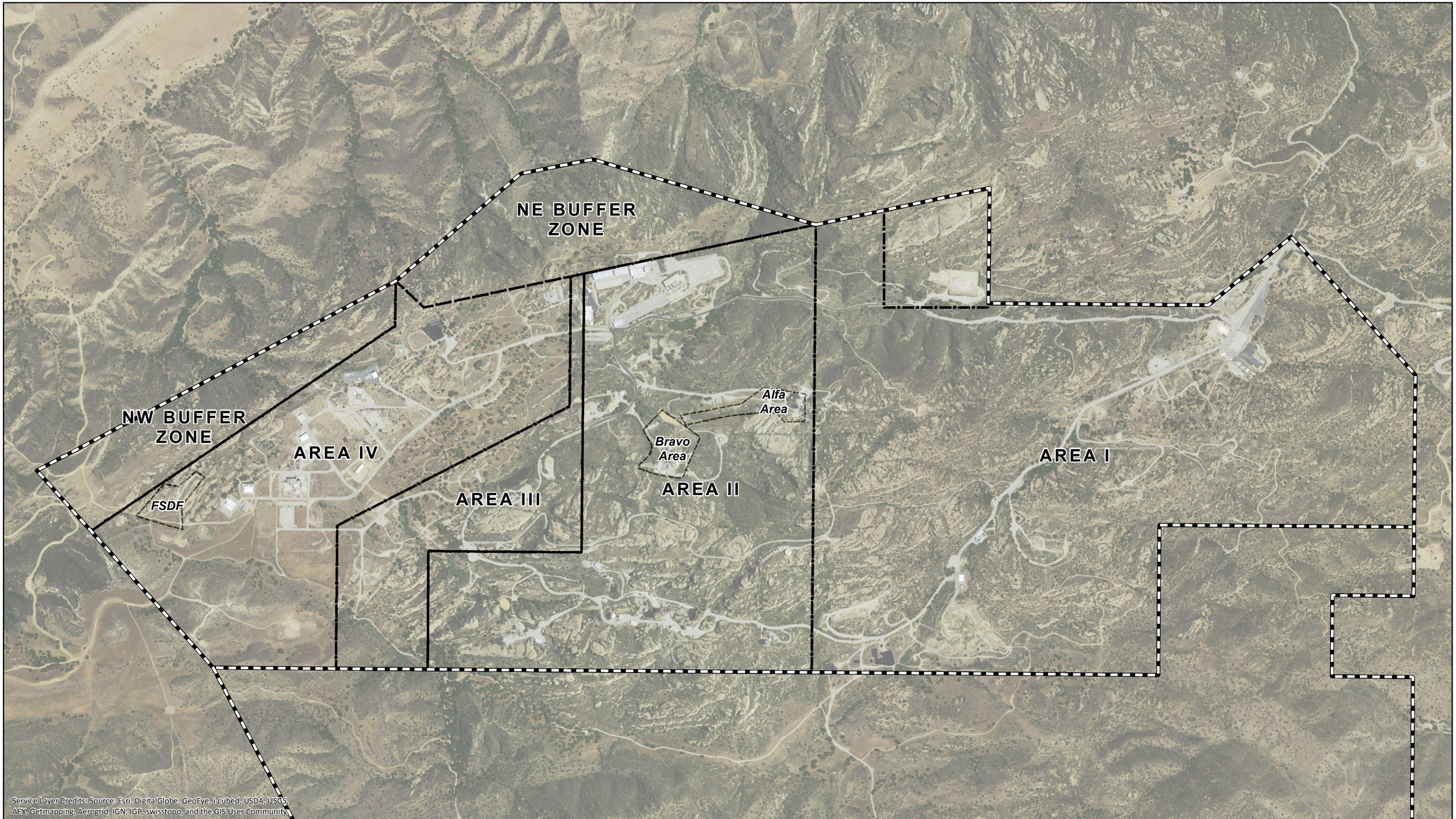
2.1 General Overview of SSFL Site Conditions

This section provides a general summary of geology and hydrogeology across the entire Site. This information is provided to establish the context of overall Site conditions. The characteristics specifically of Areas II and IV, where ISTR applicability is being evaluated, are discussed in **Sections 2.3** and **2.5** below. **Figure 2** is a SSFL geologic structures map discussed later in this paper.

2.1.1 Geology

SSFL is located in the Western Transverse Ranges physiographic of southern California. Basement rocks exposed in the Santa Susana Mountains and Simi Hills are primarily sedimentary and volcanic in origin with age ranging from Late Cretaceous to Late Pliocene. These rocks are mostly exposed except where they are covered by alluvium in some valleys and canyons. Sedimentary rocks in the region range from coarse-grained conglomerate and sandstone to fine-grained siltstone and shale (MWH, 2009b).

The Chatsworth formation is a sequence of marine turbidite that underlies most of the Western Transverse Ranges and the SSFL site. The formation is at least 6,000 feet thick and extends more than 2,000 feet below sea level in the vicinity of the Site. It is the primary rock unit exposed at SSFL (MWH, 2009b) and consists primarily of sandstone with lesser amounts of interbedded shale, siltstone and conglomerate. The formation also contains a pervasive fracture network consisting of a systematic arrangement of fractures and joints. Faults and folds tend to strike in an approximately east-west direction. Joints typically cross the full thickness of one or multiple sandstone beds, often ending at the contact with shale. Joints extending fully across thick shale units are infrequent (MWH, 2009b).


NE BUFFER ZONE
NW BUFFER ZONE
AREA IV
AREA III
AREA II
AREA I
Alfa Area
Bravo Area
FSDF
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Legend

- RI Site Boundary
- Site Area
- SSFL Property Boundary

SSFL Administrative Areas

0 500 1,000 2,000 Feet

Santa Susana Field Laboratory
Ventura County, California
Figure 1

CDM Smith

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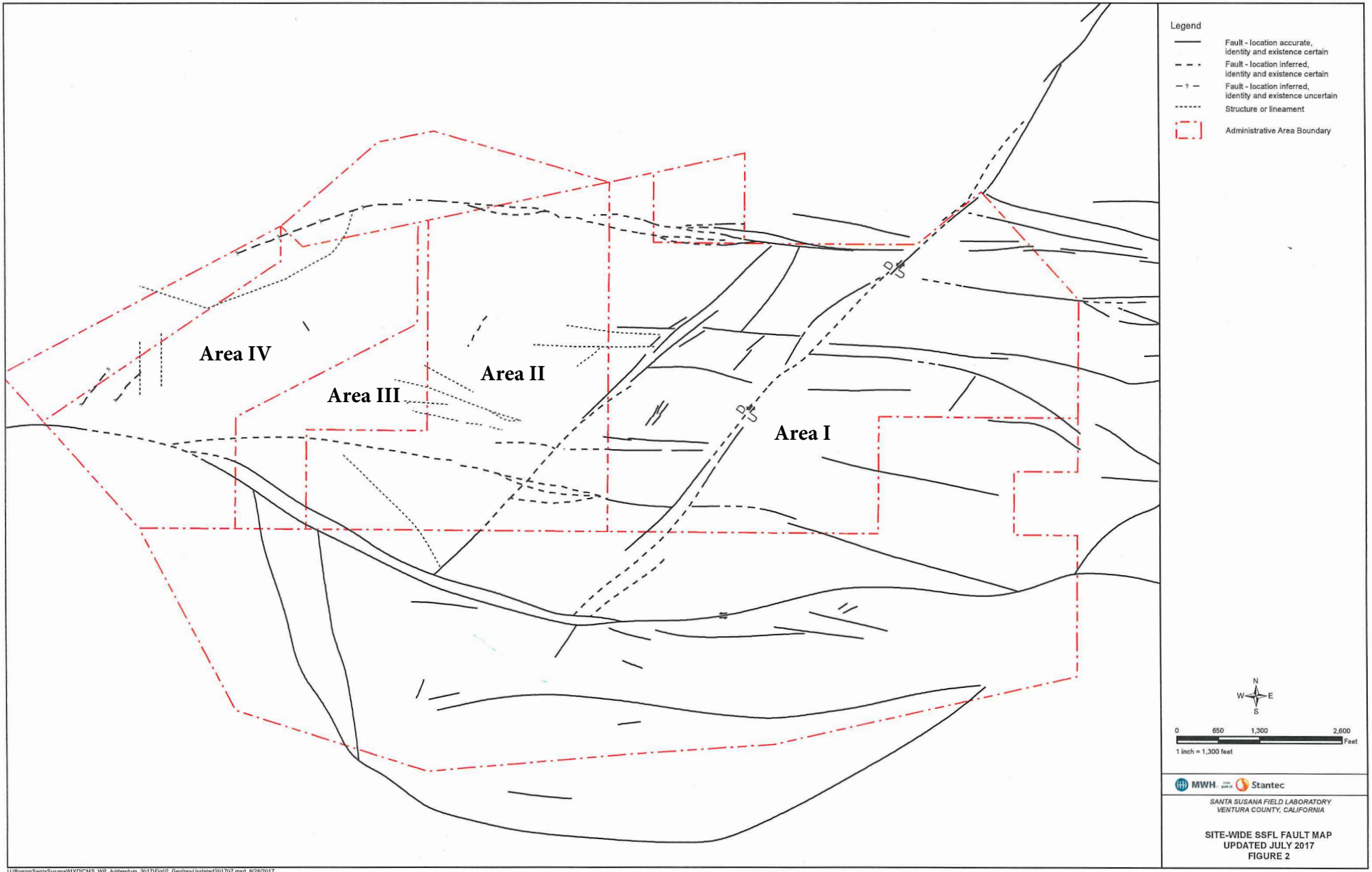


Source: MWH-Stantec 2017

Figure 2 SSFL Faults and Structures Map

The Chatsworth formation is overlain by a sequence of younger sedimentary and volcanic marine and non-marine formations. Although the entire sequence does not occur in one place, the overlying sedimentary formations from oldest to youngest are the Simi Conglomerate and Las Virgenes, Santa Susana, Llajas, Sespe, Vaqueros, Topanga, Calabasas, and Modelo/Monterey formations. The thickness of these sedimentary units is greater than 40,000 feet. Unconsolidated deposits at SSFL include alluvium, artificial fill and thin soils over bedrock; however, these deposits are typically only 1 to 15 feet thick. Areas with five or more feet of alluvium cover are rare, totaling approximately 11 percent of the SSFL site (MWH, 2009b).

2.1.2 Groundwater

When less than fully saturated conditions exist between two saturated zones, the condition of the upper zone is referred to as perched. Areas of shallow perched groundwater are documented across the Site. Typical depths to shallow perched water range from 10 to 30 feet below ground surface (bgs); thicknesses are highly variable and dependent on the annual precipitation amounts. Due to the steep downward vertical gradients detected in several wells, semi-saturated zones at depth are potentially likely but relatively deep perched zones are not currently evident (MWH, 2009b).

Groundwater primarily exists within the Chatsworth Formation bedrock beneath SSFL. The upper saturated zone is unconfined, whereas semi-confined to confined conditions may occur below aquitards and with increasing depth. Across most of the Site, the groundwater hydraulic gradient is downward regardless of the degree of confinement.

Historical groundwater production from SSFL wells indicates that portions of the Chatsworth Formation contain locally productive aquifer units. These units generally consist of fractured sandstone members, separated by thin shale and siltstone members that sometimes behave as aquitards. Major faults divide SSFL into roughly ten large blocks, which are further subdivided by shale beds. These faults influence the hydrogeological structure. Additionally, the Chatsworth Formation contains a systematic network of fractures and joints that result in a hydraulic continuum of groundwater flow through the entire system. However, the small magnitude of the bulk fracture porosity estimated for the Chatsworth Formation shows that fractures contribute little to the total rock porosity (MWH, 2009b).

The bulk hydraulic conductivity (i.e., combined matrix and fracture hydraulic conductivity) of the Chatsworth Formation fractured sandstone is several orders of magnitude greater than that associated with the unfractured sandstone matrix. Because fractures contribute heavily to the estimated bulk hydraulic conductivity when present, the estimated bulk hydraulic conductivity for SSFL ranges greatly from 10-7 to 10-2 centimeters per second (cm/s). However, the "site-wide" bulk hydraulic conductivity is estimated to be 10-5 cm/s (MWH, 2009b) and can be described as low to moderate. Due to increased overburden pressures, the bulk hydraulic conductivity is estimated to decrease with depth and eventually approaches the hydraulic conductivity of the matrix. However, this varies locally.

2.1.3 Extent of Groundwater Contamination

TCE is a primary contaminant of concern at the Site resulting from of its pervasive historical use, elevated concentrations in soil and groundwater, and its high frequency of detection. As shown in **Figure 3**, nearly seventy percent of historical groundwater samples from the Site contained TCE. The current interpretation of the extent of TCE contamination in bedrock is based on the

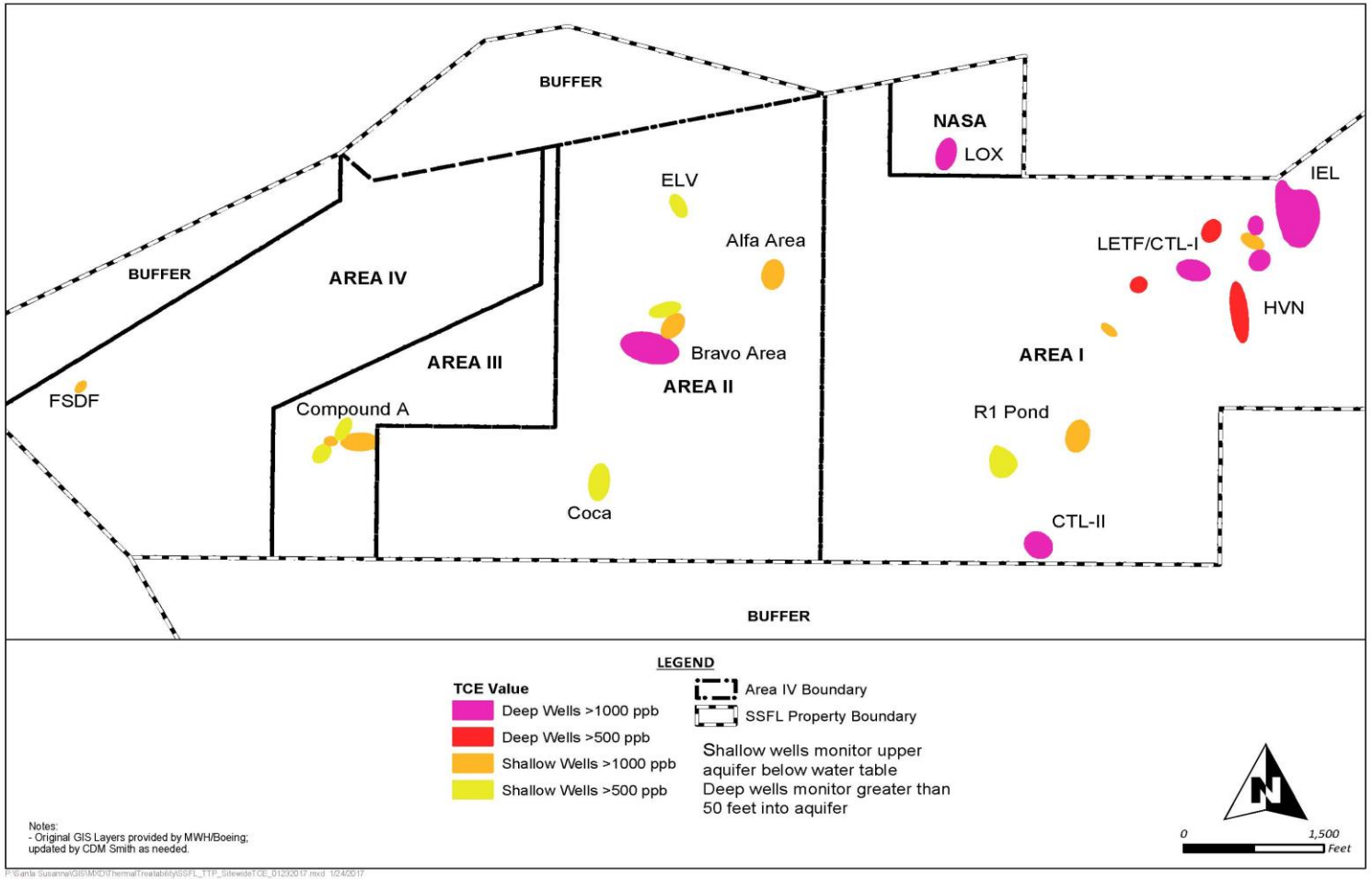


FIGURE 3
TCE in Subsurface Media at SSFL

completion depth of the local coreholes/boreholes (i.e., the maximum depth of exploration), the thickness of the vadose zone, the distance from the source areas, the documented total mass released to the ground, and the degree of penetration of immiscible phase TCE into the water table.

2.2 Area I Geology

Although Area I shares the same geologic origin as most of the remainder of SSFL – that is it is comprised of the Chatsworth Formation – Area I differs in the amount of faulting and distinct geologic structures not present elsewhere. Numerous steep to near-vertical displacement structures are present within Area I, including minor and major faults as well as deformation bands which offset existing geologic features laterally and/or vertically (MWH, 2009). Previous bedrock coring work indicated that although variable, the vertical spacing between fractures at the SSFL is between 1 to 2 feet and can exceed 20 feet. In addition, fracture density ranges up to 10 to 12 fractures per meter. It is understood that the bedrock underlying Area I is significantly more fractured than other areas at the SSFL.

2.3 Area II Geology

For the purposes of this report, Area II at the SSFL is characterized by the Alfa and Bravo AIG which is located in the central part of the Site (**Figure 3**). A number of site characterization activities have been performed at these areas and four other adjacent facilities including the Alfa/Bravo Fuel Farm (ABFF), the Storable Propellant Area (SPA), the Hazardous Waste Storage Area (HWSA) (clean closed in 1999), and the Waste Coolant Tank (WCT).

2.3.1 Geology

The Alfa/Bravo AIG is underlain by alluvium and colluvium derived from weathered bedrock that ranges in thickness from 0 to 13 feet. Bedrock in the Alfa/Bravo AIG includes various members of the Chatsworth Formation. From oldest to youngest, these members include the Sage member of Sandstone 1, Shale 2, and the lower members of Sandstone 2 (the Silvernale, SPA, Lower Burro Flats, and ELV Members) of the Chatsworth Formation (NASA, 2015). The Sage member is predominantly a medium-grained sandstone but contains minor interbeds of shale and siltstone. Shale 2 is a thinly bedded shale and siltstone and includes a middle layer of sandstone. The Silvernale member, like the Sage member, is a medium-grained sandstone with minor siltstone units. Locally, the Silvernale can contain lenticular conglomerates (MWH, 2009b). The SPA member consists of interbedded fine- and medium-grained sandstone, siltstone and shales. Bedrock formations strike northeast to southwest and dip 25 to 40 degrees to the northwest.

The primary geological structures in the Alfa/Bravo AIG are two deformation bands: the Alfa Deformation Fault and the North Bravo Deformation Band. The Alfa Deformation Fault crosses east-west through the entire Alfa/Bravo AIG, with the surface trace passing approximately between the Alfa Area and the Bravo Area. The North Bravo Deformation Band extends 800 feet, trending northwest-southeast, and south of the Bravo Area. A deformation band is defined as a structure having less than 18 inches of displacement (NASA, 2015). Other evidence of faults includes fracture zones producing over 10 gallons per minute (NASA, 2015).

2.3.2 Hydrogeology

Four hydrostratigraphic units (Sandstone 1, Shale 2, Sandstone 2 and the overburden/weathered bedrock) and two categories of groundwater (Near-surface groundwater [NSGW] and Chatsworth

Formation groundwater [CFGW]) have been defined in the Alfa/Bravo AIG (NASA, 2015). NSGW is generally found as continuous with the Chatsworth Formation groundwater (CFGW) in the Shale 2 and Sandstone 2 members although it has been encountered as perched groundwater in the Sandstone 1 member. Piezometers screened in the weathered Sandstone 1 member are generally dry. When perched NSGW is found in the weathered Sandstone 1, the water levels are up to hundreds of feet higher than those of the CFGW found in the underlying competent bedrock (NASA, 2015).

In the Alfa Area, NSGW is generally found in wells screened in weathered Shale 2 at depths ranging from 4.5 feet below top of casing (btoc) to 58 feet btoc; depth to water generally decreases from east to west (NASA 2015). In Bravo Area, NSGW is found in both weathered Sandstone 1 and Shale 2. Depth to NSGW in the northern part of Bravo Area is about 1.5 to 18 feet btoc, while to the southwest it is found from 53 to 60 feet btoc. NSGW throughout the Alfa/Bravo AIG shows small-scale seasonal fluctuations and longer-term decline in water elevations. Groundwater flow in the NSGW roughly mimics the topography and surface water drainages, flowing east to west (NASA, 2015).

Two distinct CFGW systems have been identified at the Alfa/Bravo AIG: groundwater in Sandstone 1 and groundwater in Shale 2/Sandstone 2. CFGW encountered in the Shale 2 and Sandstone 2 members is generally vertically continuous with NSGW (little vertical head difference between the two groundwater systems). The potentiometric surface of the Sandstone 1 CFGW shows a "groundwater trough" thought to have been created by recent groundwater pumping. Groundwater flows from the west and south into the trough. Groundwater in the Shale 2/Sandstone 2 is found 100 to 150 feet higher than it is found in Sandstone 1. There is an apparent groundwater "ridge" extending north from the Storable Propellant Area (SPA; Area II). Groundwater flow in the Shale 2/Sandstone 2 unit is to the northwest, north and northeast. (NASA, 2015).

Hydraulic conductivity of the NSGW in alluvium and weathered bedrock ranged from 5×10^{-6} to 6×10^{-3} cm/s. Estimates of bulk hydraulic conductivity of the CFGW ranged from 4.2×10^{-6} to 4.5×10^{-2} cm/s based on packer tests. Although there is some uncertainty (with respect to packer test data quality), the data suggest a higher bulk hydraulic conductivity in the deeper intervals of monitoring well RD-04. The bulk hydraulic conductivity of the Shale 2/Sandstone 2 is 2 to 3 orders of magnitude lower than that of the Sandstone 1 member (NASA, 2015).

2.3.3 Extent of Contamination

The Alfa and Bravo Test Areas were used to test rocket engine in the mid-1950s; TCE was used to flush the piping before and after the tests. Approximately 85,500 gallons of TCE were released into the ground including approximately 68,400 gallons in the Alfa Test Area and approximately 17,100 gallons in the Bravo Test Area (Rockwell, 1984, NASA, 2015). Other COCs in the Alfa/Bravo AIG include degradation products of TCE (cis-1,2-DCE, trans-1,2-DCE, and vinyl chloride) as well as carbon tetrachloride, N-nitrosodimethylamine, and 1,4-dioxane (NASA 2015).

The known source areas (where TCE was released into the environment) includes the four retention and skim ponds, the test stand areas, the drainage pathways from the test areas to the ponds, the western SPA area, tank storage areas at ABFF, the Alfa Spray fields, and an area near

pumping well WS-09 (there were no known spills in this areas) (NASA, 2015) (**Figure 3**). Although non-aqueous phase liquid (NAPL) has not been found in the AIG, there are some indications of NAPL in the pond areas (elevated vapor instrument readings of soil cores), and dissolved concentrations in WS-09 exceed 1 percent of the solubility limit (NASA 2015) are indicative of the possible presence of NAPL in the subsurface.

The horizontal extent of the TCE plume in the NSGW is restricted to two separate plumes in the Alfa and Bravo Test Areas. In the Alfa Area, the plume is elongated parallel to the direction of the Shale2 beds. In the Bravo Area, groundwater plume is roughly triangular and extends from WS-09 on the west, RD-04 on the east and PZ-070 on the north. A distinct fracture zone at elevations between 1,525 amsl and 1,570 amsl may also serve a significant transport pathway.

The CFGW groundwater plume is collocated with, but larger than, the NSGW plumes. In addition, the plume is continuous between the Alfa and Bravo Areas and the lateral extent has not been defined (NASA, 2015).

The vertical extent of TCE contamination has not been fully delineated. The highest TCE concentration in groundwater of 21,000 microgram per liter (µg/L) was found in WS-09 in 2013 (NASA, 2015); however, this borehole is open to a depth of 800 feet bgs. A rock core was drilled in the Alfa Test Area to approximately 400 feet bgs as part of a source characterization (Hurley et al., 2003). Concentrations of TCE in bedrock matrix pore water were found to be higher in the pore water from the saturated zone compared to the vadose zone. Peaks in highly discretized pore water samples indicated that TCE concentrations were found:

- in the vadose zone at a depth of about 150 feet bgs with a maximum concentration of approximately 1,000 µg/L;
- near the water table at depths between 290 and 305 feet bgs with a maximum concentration of about 1,250 µg/L; and
- between 355 and 390 feet bgs with a maximum concentration of approximately 5,450 µg/L (at approximately 386 feet bgs).

The pore water concentrations appear to be increasing with depth. However, the borehole was terminated at a depth of 400 feet bgs, just below the maximum pore water concentration.

In 2013, TCE was observed at RD-49 at 180 µg/L between approximately 248 and 298 feet bgs and 1.2 µg/L between approximately 508 to 558 feet bgs. This suggests that the zone of TCE contamination exceeding 5 µg/L is between approximately 298 feet and 558 feet bgs.

2.4 Area III

Area III is "nestled" between Areas II and IV and shares geologic conditions as these two areas (see **Figure 2**). The primary geologic feature is the Burro Flats and Coca faults within the southern part of Area III. Like Area IV, Area III would be expected to exhibit a less fracture density, compared with Area I. The Boeing Site-wide Groundwater RFI Report (MWH, 2017) provides the details for the hydrogeology and extent of VOC contamination for Area III.

2.5 Area IV

For the purposes of this paper, VOC impacted bedrock within Area IV at the SSFL is being characterized by the Former Sodium Disposal Facility (FSDF) which is located in the western part of SSFL (**Figure 2**). The FSDF consisted of three facilities for cleaning of liquid sodium and potassium from metal objects including an asphalt and concrete pad used for steam cleaning objects, an adjacent concrete submergence pit (pool), and a pond. Historically, a number of site characterization and remediation activities have been performed in this area to remediate a variety of chemicals including TCE. Remediation activities included the removal and replacement of all surface soil. However, no remedial action has been performed to address TCE contamination in groundwater. Groundwater sampling data are provided in the Area IV GW RI Work Plan (CDM Smith, 2015a).

2.5.1 Geology

Because of remedial efforts, surficial soil at the FSDF area is mostly local, imported fill material consisting of typically fine-grained silty sands from weathered Chatsworth and Santa Susana Formations. The FSDF site is located over the Chatsworth Formation that consists of three major stratigraphic units. From oldest to youngest these units are the Sandstone 1, Shale 2, and Sandstone 2 units. Stratigraphically, the FSDF lies within a medium-grained sandstone member of the upper Chatsworth Formation known as the Upper Burro Flats member (MWH, 2006). Beneath the Upper Burro Flats member is the ELV member which consists of thinly interbedded fine-grained sandstone, siltstone, and shale. The Lower Burro Flats member underlies the ELV member and it predominantly consists of medium-grained sandstone with significant siltstone/shale interbeds (CDM Smith, 2015b).

Two geologic structures are present within the FSDF area (see **Figure 2**) that may have an influence on groundwater flow and contaminant fate and transport (CDM Smith, 2015b). The Burro Flats fault in the southern portion of the FSDF area strikes approximately east-west at this location. Two features defined as the Western and Eastern FSDF Structures strike approximately north-south in the eastern portion of the study area. A series of deformation bands are also present that strike approximately northeast-southwest and have currently been defined to comprise the western extent of the North Fault zone (MWH, 2006).

2.5.2 Hydrogeology

In the FSDF area, NSGW is perched above Chatsworth Formation. When present, NSGW is encountered at an average depth of approximately between 7.6 feet bgs to 22.7 feet bgs. The NSGW in the FSDF area is laterally discontinuous and has limited aerial extent. Depth to Chatsworth Formation groundwater in the FSDF area is quite variable due to several physical conditions present in the area. Perched groundwater above the Chatsworth Formation can be found as shallow as 25 feet bgs (currently dry) whereas depth to groundwater in the Chatsworth Formation can be up to 345 feet bgs (MWH, 2009b).

Hydrographs from several wells demonstrated variable fluctuations in water levels due to varying storage capacity of the bedrock. Although the transmissivity profile from Corehole-8 in the FSDF area failed, multiple slug tests were performed in FSDF wells. In general, the bulk hydraulic conductivity of the bedrock ranges from 10^{-6} to 10^{-5} cm/s and is considered low compared to other Site bedrock. The groundwater system in the FSDF area receives reduced

recharge in most years when the average annual precipitation is less than about 15 inches per year (MWH, 2009b). Approximately 2 inches per year of the average annual precipitation of 18.8 inches is the estimated recharge to the groundwater system within the FSDF area. The rate of decline in groundwater levels after recharge is about 15 percent of the rate of rise.

Hydraulic tests confirm that the Chatsworth Formation in the FSDF study area is interconnected both vertically and laterally. Pumping test results were used to determine the geometric mean hydraulic conductivity value of about 6×10^{-7} centimeter per second (cm/s). Slug tests resulted in a geometric mean hydraulic conductivity value of 5.4×10^{-6} cm/s. This shows that the fracture network at the FSDF leads to little appreciable increase in the bulk hydraulic conductivity of the Chatsworth Formation. Laboratory measurements of the bedrock show that the porosity of the bedrock beneath the FSDF is approximately 14 percent and the matrix permeability is 2.6×10^{-7} cm/s (MWH, 2009b).

2.5.3 Extent of Contamination

Near surface (meaning surface soils down to bedrock) sources of TCE and other VOCs in shallow FSDF soil were removed during two separate excavations of about 10,000 cubic yards of soil conducted in 1992 and 2000. Since excavation, the highest groundwater concentration observed for RS-54 installed to the top of competent bedrock was 4,500 µg/L in 1994 and 1,600 µg/L in 2014. This well is currently dry. TCE concentrations in Chatsworth Formation bedrock well RD-64 was 680 µg/L in 2001 and 14 µg/L in 2016. All indications are that the majority of the TCE mass remains in shallow bedrock (<50 feet bgs) at the RS-54 location.

In order to gain discrete porewater data from the bedrock matrix, corehole 8 (C-08) was drilled in the bedrock within the area of the former Lower Pond at the FSDF where TCE and other VOCs were believed to have entered the ground. Rock core samples showed that nearly all of the TCE mass encountered was found in the vadose zone at this location, with a maximum TCE concentration of about 53,000 µg/L measured in porewater. Below the water table, which was encountered at a depth of about 180 feet, TCE was detected in only three rock core samples, with a maximum TCE concentration of 350 µg/L in porewater. The highest concentrations of TCE detected in rock core were below the aqueous solubility of TCE of approximately 1,100 milligrams per liter (mg/L). These results combined with groundwater data suggest that dense non-aqueous phase (DNAPL) TCE is no longer present at the FSDF.

Near-surface groundwater monitoring results from wells and piezometers showed that the TCE plume exceeding 5 µg/L covers approximately 4 acres of the FSDF study area. The TCE plume in the Chatsworth formation is believed to result from both vapor transport from the bedrock vadose zone and dissolved aqueous phase transport via recharge waters. The lack of immiscible phase TCE flow through the fracture network into and below the saturated zone in bedrock can be attributed to a relatively small volumetric release and/or small fracture apertures (MWH, 2009b). The estimated plume extent with TCE concentrations greater than 100 µg/L is likely less than 30,000 square feet; any potential target treatment area for ISTR in Area IV would be within this footprint, possibly targeting a higher concentration zone within this footprint.

Section 3

Thermal Treatment Technologies: General Concepts & Technology Screening Evaluation

A "state-of-the-practice" thermal technologies evaluation was performed to provide a comprehensive literature review to capture the fundamental principles, laboratory experimental studies, modeling exercises, optimization studies, and field implementations of thermal treatment for volatile organic compounds in the subsurface. The initial search included key words such as *in situ* thermal remediation, electrical resistance/resistive heating, thermal conduction/conductive heating, steam-enhanced extraction, chlorinated solvents, and bedrock. Results from this search, which include numerous peer-reviewed journal articles, conference proceedings, and book chapters, were subsequently screened to eliminate irrelevant search results. Following the initial search, a series of literature searches focusing on the individual thermal technologies were performed. In addition, case studies from the most prominent thermal technology vendors were obtained. The acquired literature was used to develop a fundamental understanding of state-of-the-practice of ISTR technologies. The general concepts of several ISTR technologies are summarized in **Section 3.1**. Reports and case studies on ISTR field implementation specifically targeting treatment of chlorinated solvents in bedrock lithologies were used to determine the applicability of different techniques for *in situ* remediation at the Site. A summary of these case studies is provided in **Section 5**. In addition to the case studies, the primary "state-of-the-practice" sources reviewed in developing this evaluation include:

- U.S. EPA Groundwater Issue – How Heat Can Enhance *In Situ* Soil and Aquifer Remediation: Important Chemical Properties and Guidance on Choosing the Appropriate Technique – EPA/540/S-97/502. April 1997 (U.S. EPA, 1997)
- Environmental Security Technology Certification Program (ESTCP) Final Report – Critical Evaluation of State-of-the-Art *In Situ* Thermal Treatment Technologies for DNAPL Source Zone Treatment – ER-0314. January 2010 (ER-0314, 2010)
- ESTCP Final Report – Dense Non-Aqueous Phase Liquid (DNAPL) Removal from Fractured Rock Using Thermal Conductive Heating (TCH) – ER200715. August 2012 (ER200715, 2012)
- U.S. Army Corps of Engineers Design: In Situ Thermal Remediation – EM 200-1-21. May 2014 (EM 200-1-21, 2014)
- U.S. EPA – *In Situ* Thermal Treatment Technologies: Lessons Learned. 2014
- Federal Remediation Technologies Roundtable: Frtr.gov
- Vendor websites: Terratherm.com & Thermalrs.com

This section also provides a preliminary screening evaluation of ISTR technologies that should be further evaluated for field implementation at the Site. Details are provided in the subsequent sections.

3.1 Description of Thermal Treatment Technologies

A brief description of the fundamental principles and conceptual design of the most commonly-employed thermal remediation technologies is presented herein. The following discussions address the technologies of electrical resistance/resistive heating (ERH), thermal conduction/conductive heating (TCH), steam-enhanced extraction (SEE), vitrification, radio-frequency heating, hot air injection, hot water injection, and other uncommon/novel techniques. Where appropriate, discussion of each of the aforementioned technologies will be presented with regard to their applicability at the Site.

There are many common elements to all of these ISTR technologies, as the primary goal is to heat up the subsurface to enhance contaminant mobility and hence extraction. Unless discussed specifically in the individual technology description, these common elements are considered to be present in each of the ISTR technologies discussed below.

1. ISTR aims to heat up the groundwater and/or subsurface through several techniques. Through heating, the properties of the NAPLs (and dissolved-phase contaminants) will change, allowing for easier extraction via a vapor and/or liquid extraction system. The primary thermodynamic changes that will occur in NAPL through heating include: increased solubility (decreased surface/interfacial tension), decreased viscosity, increased vapor pressure and potential volatilization, and decreased density. These changes will increase NAPL mobility and/or volatilization, allowing for easier removal.

2. With the exception of certain contaminants (e.g., 1,1,1-trichloroethane, pesticides), *in situ* contaminant destruction (e.g., hydrolysis, oxidation, mineralization, and pyrolysis) is not the intended goal of ISTR. Instead, contaminants are mobilized via the change in thermodynamic properties (see above) and then are removed from the subsurface via a vapor and/or groundwater extraction system. The contaminant streams are then treated above-ground. The above-ground treatment applications are therefore more dependent on the contaminants extracted than the ISTR implementation method.

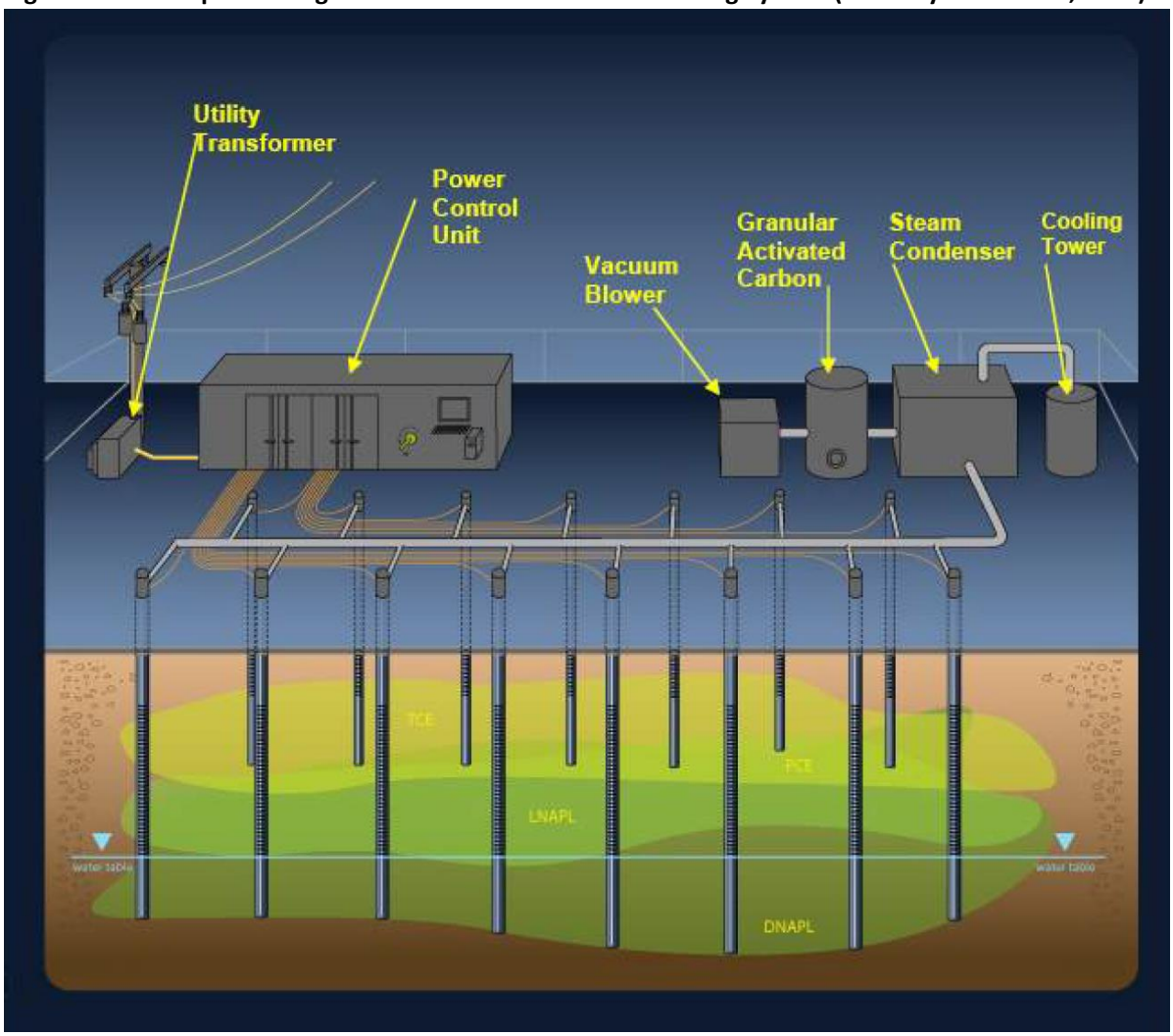
3. Enhanced abiotic and biotic degradation of certain contaminants is often observed related to elevated aquifer temperatures following ISTR. In fact, new methods are currently being used that apply low temperatures to the subsurface for the primary goal of enhancing these abiotic and biological degradation mechanisms (ER-200719), as discussed in **Section 3.1.8.**

3.1.1 Electrical Resistance Heating

Developed by the DOE, ERH was first used in the oil and gas industry but has since been applied to enhance contaminant removal in soil, sediment and/or bedrock in the field of environmental remediation. The technology involves heating the target subsurface volume by the passage of electrical current through saturated and unsaturated zones among the array electrodes. The resistance to electrical current causes the water and subsurface material in the formation to heat up until its boiling point is reached, also resulting in increased subsurface temperature. Because water is required for ERH to operate as it is the conductive material that the electrical current passes through, ERH is not generally able to increase the subsurface temperature above the boiling point of water. Once the water boils, the conductive material is no longer present. Therefore, contaminants with boiling points lower than the boiling point of water (such as TCE)

will be vaporized once their boiling point is reached. Contaminants with boiling points higher than water (chlorobenzene, tetrachloroethene [PCE], etc.) will not be vaporized and may not be completely removed from the subsurface through ERH. Although the resistivity in subsurface materials can vary greatly, heating of soil or rock will occur as the subsurface temperature approaches the boiling point of water (EM-200-1-21-1, 2014). ERH has been applied extensively at sites worldwide for treatment of a wide variety of contaminants including VOCs, chlorinated VOCs (CVOCs), pesticides, PAHs, and creosote.

Figure 4. A Conceptual Design of an Electrical Resistance Heating System (courtesy of ER-0314, 2010)



The conceptual design schematic for a typical ERH application is illustrated in **Figure 4**. The three main elements of an ERH system are the heating system, extraction system (vapor and/or multi-phase) and treatment system for extracted vapor, liquid and/or NAPL. Other elements of an ERH system include temperature and pressure monitoring equipment, a power control unit (PCU); and a computer control system. Specifically, the electrodes are typically constructed of steel pipe or copper plates, although sheet pilling has been used in some applications. Multiple electrodes may be installed within the same electrode boring to allow for targeted treatment of multiple discrete depth intervals. Steel pipe electrodes can be installed in a manner similar to installation of a typical monitoring wells. A conductive material such as graphite and/or steel shot may be used to pack the annulus of the borehole in depth intervals of interest to increase the effective

conductive radius of each electrode. On the other hand, at depth intervals where heating is not desired, the electrode construction materials are insulated and the surrounding borehole annulus is filled with relatively non-electrically conductive materials such as sand or cement.

The vapor and/or multi-phase recovery system collects, condenses, and/or cools the generated steam and liquid to ambient temperatures, separates NAPL and conventional techniques are then used to adsorb or destroy the vapor and liquid phase contaminants. The PCU, which includes isolation transformers, is used to provide three or six separate electrical phases and to force the electrical current to flow between the electrodes. Three-phase heating provides a simple method to provide uniform voltage potential among electrodes emplaced in an irregularly shaped treatment area. Six-phase electrode layout, on the other hand, is often applied to a circular treatment area. In ERH, heating can be applied to separate subsurface zones either independently or in unison. In many ERH applications, especially those with significant vadose zones, the use of a drip source of potable water that is applied to soil immediately surrounding the electrodes to keep the soil adjacent to the electrodes from drying out and thus becoming less conductive.

ERH technology relies on the heating of subsurface, volatilization of groundwater, steam stripping of contaminants, and above-ground vapor recovery and treatment to remove contaminant mass. ERH typically requires between 2 to 8 weeks to reach the boiling point of water, which is the maximum achievable temperature for ERH. ERH has mostly been used for remediation of sites contaminated with NAPL (chlorinated solvents and to a smaller extent, fuels). Sites with a high groundwater flow may result in significant heat loss, although engineered hydraulic controls can help mitigate this issue. Contaminants with high boiling points (e.g., PAHs with boiling points exceeding 300°C) tend to be sorbed to soil matrices and generally immobile in groundwater, even at temperatures achievable by ERH, which limits the applicability of ERH for these contaminant types. However, increasing the temperature to the boiling point of water will result in increased mobilization of NAPL as its viscosity and density decrease and its solubility and vapor pressure increase due to the rising temperature. The mobilized NAPL – although not vaporized – can be extracted from the subsurface via a multi-phase extraction system.

Based the literature review, ERH is a potentially applicable remediation option at the Site as it has been demonstrated to be effective for treatment of chlorinated solvents in bedrock settings. ERH was therefore selected for further discussion in the subsequent sections.

3.1.2 Thermal Conduction Heating

TCH, also often referred to as in situ thermal desorption, involves the use of conduction heater wells and vapor and/or multi-phase extraction to remove contaminants. The technology relies on heater wells that are operated at high temperature (up to 800˚C) and rely on conduction to propagate heat out into the subsurface formation. During the TCH process, electrical current is run inside heater wells and the subsurface surrounding the heater wells is heated via thermal conduction (to temperatures up to 800°C). This heating creates significant temperature gradients in the formation between heater wells resulting in a heat front moving towards the lower temperature areas of the subsurface. The thermal conductivities of a wide range of subsurface materials including gravel, silt, and clay vary only by a factor of 3. Therefore, the application of heat using TCH is generally uniform across different lithologic or bedrock types and can potentially impact the entire treatment area more effectively than other in situ thermal remediation techniques that rely on distribution of energy based on hydraulic, pneumatic, and/or

electrical conductivities. This allows for more predictable treatment duration and treatment performance. However, groundwater flow through the treatment zone can impact the ability for the subsurface to heat up as all of the energy is transferred to the water entering the zone.

TCH has been employed for full-scale remediation of a variety of contaminants ranging from low boiling temperature VOCs and chlorinated VOCs, to high boiling temperature PAHs, and to recalcitrant compounds such as PCBs and dioxins. It can treat a wider range of contaminants than ERH or steam injection because temperatures significantly greater than the 100°C can be reached, thereby decreasing viscosity/density and increasing vapor pressures (allowing for volatilization) and solubility greatly. This technology has been successfully implemented for treatment in both the vadose and saturated zones and in varying lithologies including low-permeability silt and clay, and fractured bedrock. A conceptual design of an *in situ* thermal desorption system is graphically depicted in **Figure 5**.

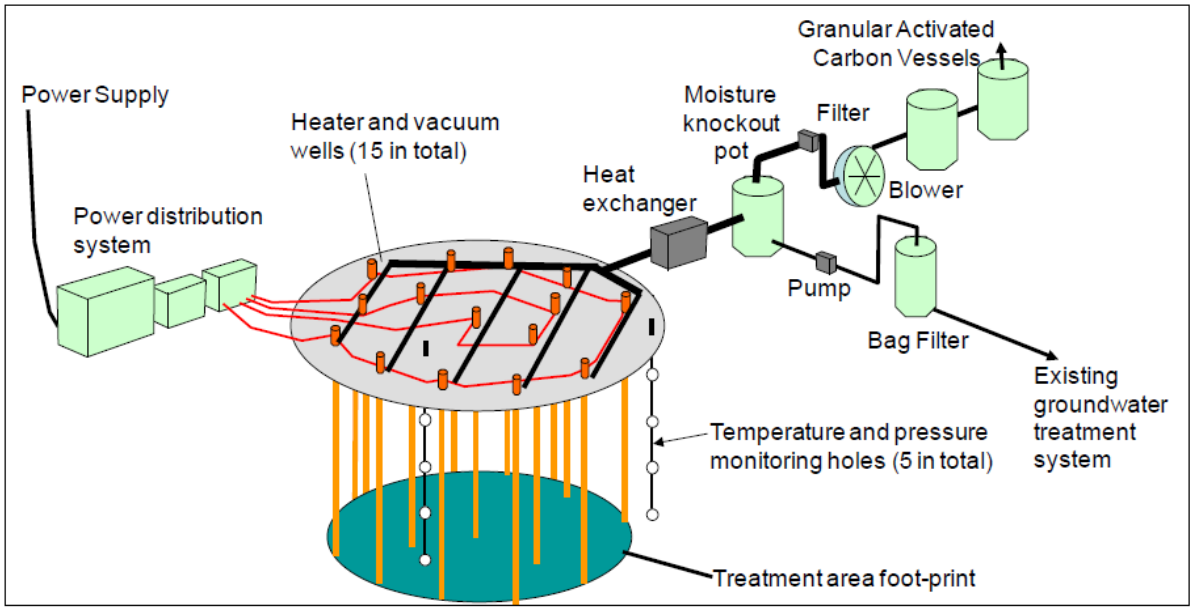


Figure 5. A Conceptual Design of an *In Situ* Thermal Desorption System (courtesy of ER-0314, 2010)

Typical operational phases of TCH, using the boiling point of water as an example and VOCs as the contaminants of concern, are illustrated in **Figure 6**. The extraction phase is typically used to document the efficacy of the pneumatic and hydraulic (if needed) control units as wells as the off-gas treatment system. During the heat-up phase, power is delivered into the heater wells to facilitate gradual heating of the subsurface to target temperature, resulting in contaminant extraction and convection of heated fluids such as steam, air, and water. The polishing phase is primarily where *in situ* steam-enhanced extraction and subsequent removal of contaminant mass occurs. Interim and final confirmation soil sampling typically occurs in latter stages of the polishing phase. Once the target remedial goals have been satisfactorily met (determined either by actual sampling or by monitoring and modeling of contaminant mass removed), the cool-down phase commences where steam is removed from the subsurface and the site is cooled to an acceptable temperature. Following the cool-down phase, *in situ* thermal desorption equipment and other infrastructure are decommissioned and demobilized from the site.

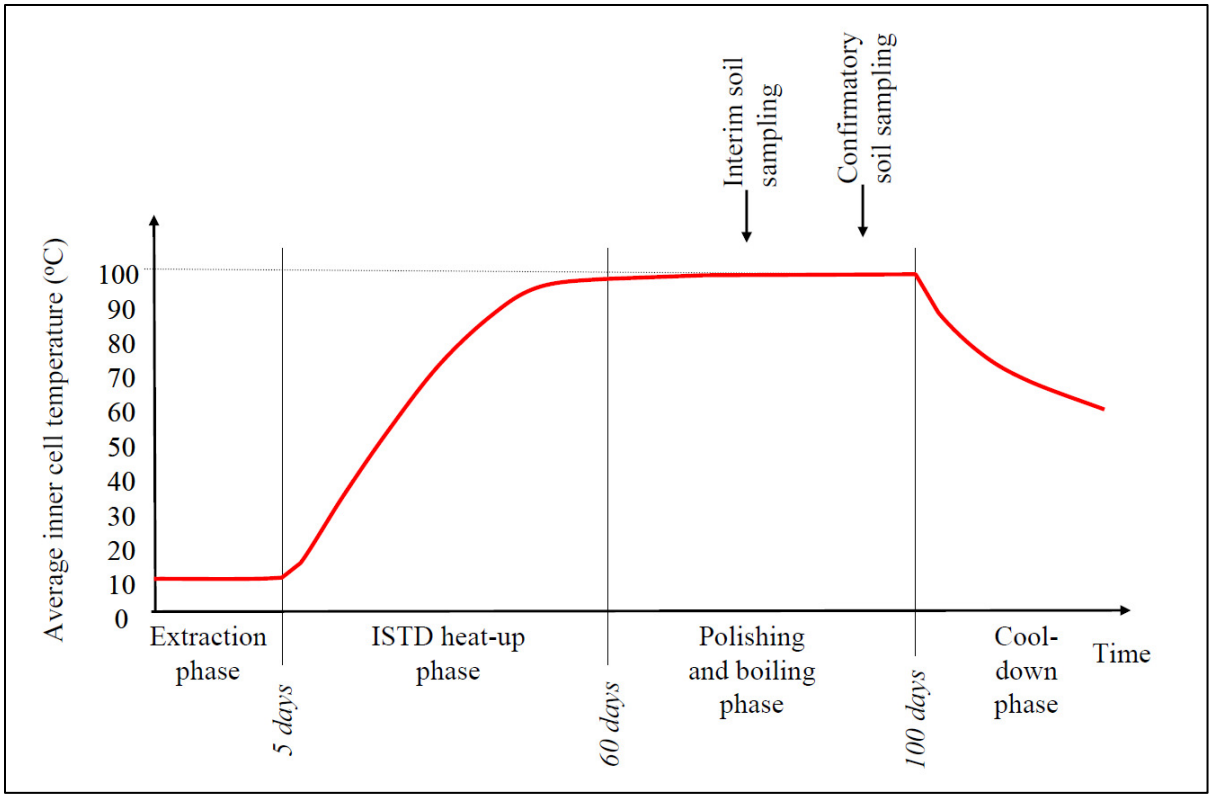


Figure 6. Typical Operational Phases of an *In Situ* Thermal Desorption System (courtesy of ER-0314, 2010)

Steam stripping and vaporization are effective contaminant-removing mechanisms for compounds with a boiling point of less than 150˚C and therefore the boiling point of water (i.e., 100˚C) is often used as the target subsurface temperature. A higher target temperature ranging between 200˚C to 350˚C is often desired for semi-volatile organic compound (SVOCs) such as polychlorinated biphenyls (PCBs), coal tar, creosote, and PAHs. At these elevated temperatures, accelerated kinetics of oxidation and pyrolysis often result in higher *in situ* destruction efficiency and thus sites are rarely heated beyond 350˚C.

Similar to ERH, TCH is a potentially applicable remediation option at the Site as it has been demonstrated to be effective for treatment of chlorinated solvents in bedrock settings. TCH was therefore selected for further discussion in the subsequent sections.

3.1.3 Steam-Enhanced Extraction

Steam-enhanced extraction (SEE) technique involves the use of a network of injection and extraction wells to introduce steam into the formation to raise subsurface temperatures up to the boiling point of water. Steam injection methods were started in the oil industry to enhance crude oil recovery and similar techniques have been adapted for recovery of contaminants in the environmental industry. Because this technology has been used extensively in the oil industry, the mechanisms have been studied extensively and are well understood (ESTCP, 2009). The addition of steam creates a pressure gradient allowing for recovery, reduced viscosity to mobilize more NAPL, and to increase the vapor pressure. This heating results in mobilization and evaporation of contaminants towards the center of a treatment system for extraction. A conceptual design of a SEE system is presented in **Figure 7**.

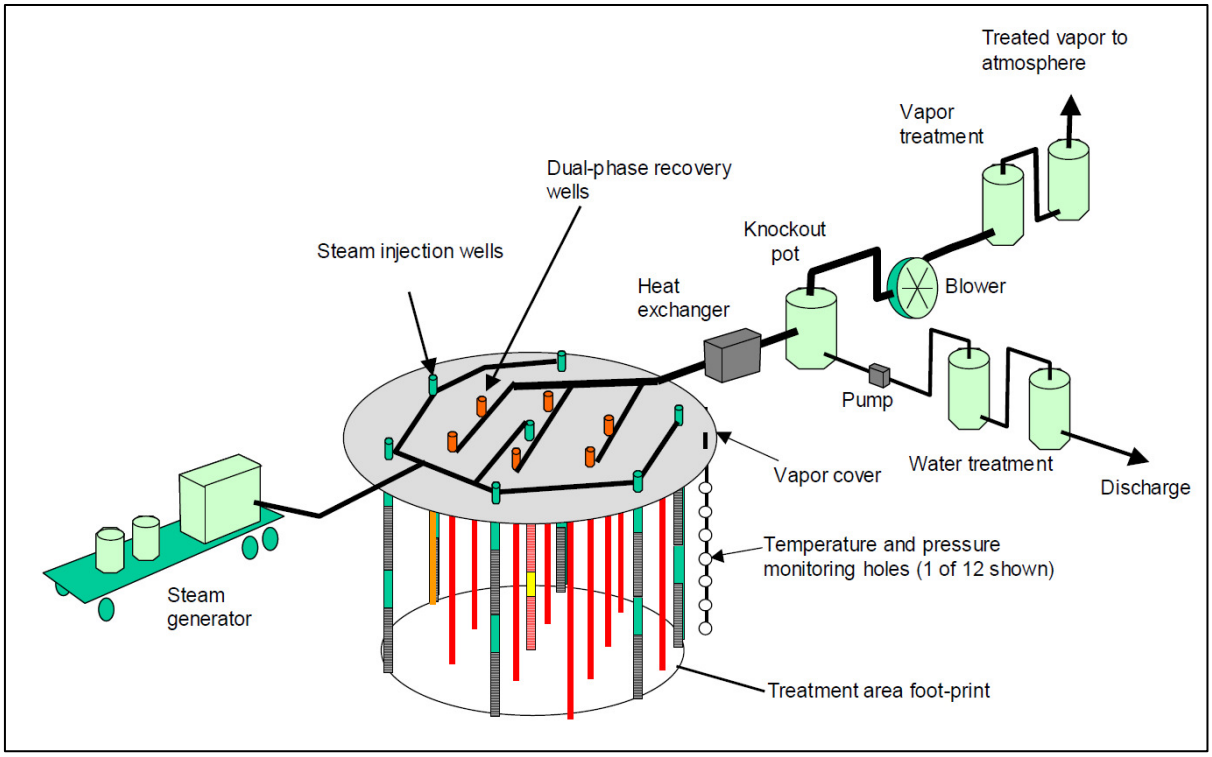


Figure 7. A Conceptual Design of a SEE System (courtesy of ER-0314, 2010)

A typical SEE operational period, using the boiling point of water as an example, is illustrated in **Figure 8**. It includes four primary phases: extraction, SEE heat-up, pressure cycling, and cool-down. The initial extraction phase does not include steam injection - it is intended to demonstrate the efficacy of the pneumatic and hydraulic control system as well as the off-gas and water treatment system. Then during the heat-up phase, steam is injected into the subsurface at a pre-determined rate to heat the target treatment area and to achieve steam breakthrough at the extraction wells. This "steam sweep" phase allows the subsurface temperature to approach steam temperature. Once target temperatures are being approached, a pressure cycling phase is implemented. During the pressure cycling phase, pressures are varied, which creates a thermodynamically unstable condition that generates steam in the subsurface, allowing for steam-stripping and resulting in removal of site contaminants. This phase maximizes the contaminant removal. The cool-down phase commences upon confirmation of satisfactory remedial goals. Interim and final soil confirmation sampling are often conducted to determine treatment effectiveness.

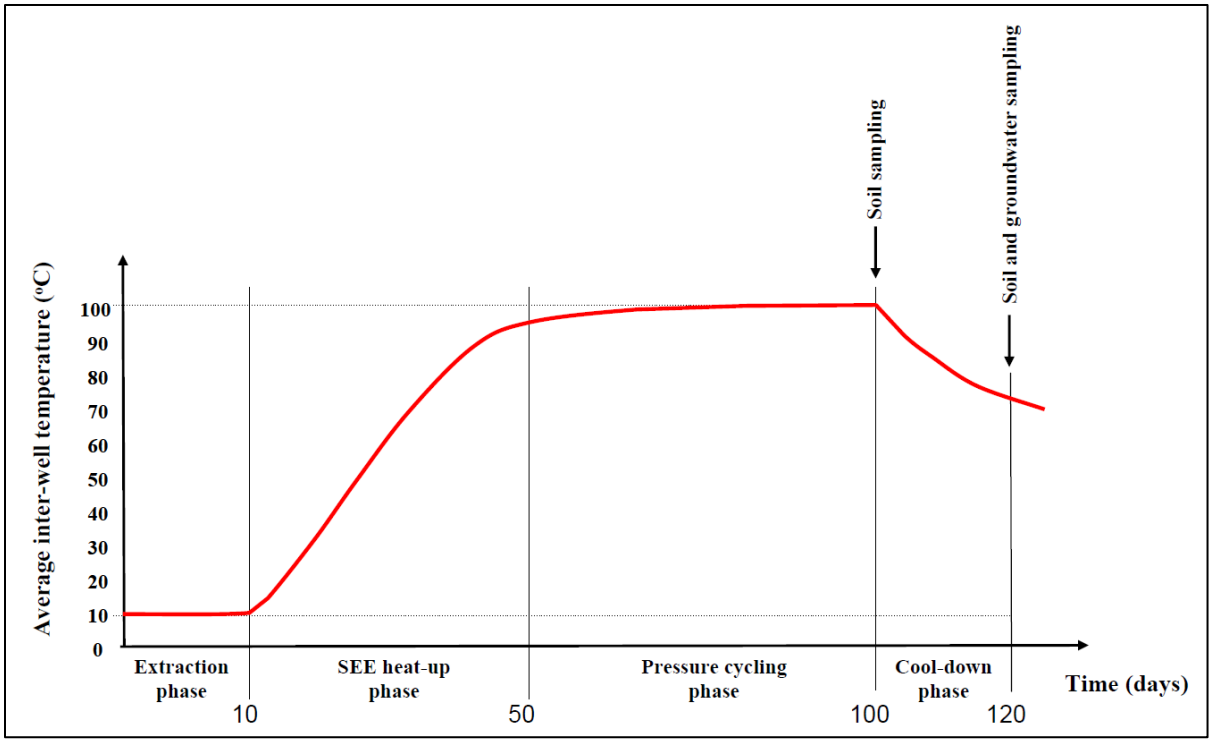


Figure 8. A Typical SEE Operational Period (courtesy of ER-0314, 2010)

SEE may represent an attractive remedial option at sites with a large contaminant mass, high contaminant concentrations, and the presence of light non-aqueous phase liquid (LNAPL) above the water table and in shallow aquifers. The technology is suitable for a variety of contaminants including CVOCs, DNAPL, and creosote. Although literature suggests that SEE may be applicable to fractured bedrock sites, SEE is generally not effective at sites predominated by low-permeability materials such as clay, fine silt, and competent bedrock because SEE relies on transport of steam in conductive pathways (i.e., fractures) as opposed to thermal or electrical conductivity within the soil, groundwater and/or bedrock matrix. Only three pilot demonstrations in fractured bedrock have been reported to date with varying success. In addition, since it is very difficult to predict and control the flow path of the injected steam, it is often more challenging to predict contaminant removal efficiency in SEE than in ERH or TCH applications. However, SEE may be used in combination with ERH and TCH to facilitate enhanced contaminant mobility and recovery and thus will be further evaluated in the subsequent sections.

3.1.4 Vitrification

Vitrification uses large quantities of electric current to convert contaminated soil and sediment into a vitreous and crystalline material. During this process, materials are often heated above 1,500°C, which degrades organic contaminants via pyrolysis and dechlorination reactions, or locks them into a matrix with no leachability. The process can be performed *in situ* or *ex situ* although it is likely limited to very shallow depths in *in situ* applications. The technology is suitable for nearly all contaminants including CVOCs, PAHs, heavy metals, and radionuclides. Because of its extremely high treatment unit cost, vitrification has not been widely implemented in full-scale settings. When it is, it is primarily intended for *ex situ* solidification and stabilization of radionuclides and heavy metals. For example, vitrification with nanometallic Ca/CaO amendments was used for immobilizing simulated radionuclide Cesium-133 in soil at the

Fukushima I Nuclear Power Plant in Japan (Denton, 2012). Vitrification technique was also used to immobilize soil contaminated with chromium and other heavy metals as well as asbestos. It should be noted that extraction and ex-situ treatment are generally not required with vitrification because the contaminants are either destroyed *in situ* or immobilized by turning the treatment area into a glass/crystalline material that is not leachable. Vitrification is less appropriate for treatment of chlorinated solvents at the Site due to the depth of contamination, the subsurface materials, the high cost to vitrify bedrock, and the lack of demonstrated reliability of the technology and therefore will not be retained for further evaluation.

3.1.5 Radio-Frequency Heating

Radio-frequency heating (RFH) involves the use of electromagnetic radiation to deliver controlled heating to the subsurface to stimulate contaminant removal. During RFH, the electromagnetic field is directed toward a non-conducting material (i.e., bedrock) and interacts with the electrically-charged particles within the subsurface, resulting in heating of the materials in a manner similar to a microwave oven (but at a lower frequency). A portion of the applied electromagnetic energy is transmitted through the material, a portion is reflected, and the remainder is absorbed. This absorbed energy is what heats the groundwater and/or DNAPL. RFH can be applied in both saturated and unsaturated soils and thus can increase temperatures in all media (including liquids and bedrock) anywhere from a few degrees above ambient temperature to more than 300°C depending on the application. Because it heats the subsurface similar to other thermal techniques, RFH supports the removal of contaminants by enhancing their mobility and water solubility, increasing vapor pressures, and decreasing viscosity, surface tension, and/or interfacial tension. In addition, directional application of RFH makes targeted treatment much more applicable compared to ERH, TCH, and SEE.

Theoretically, RFH can be deployed at depths ranging from 10 feet to greater than 300 feet with well spacing between 10 and 50 feet. Because it can be targeted, it can be performed more efficiently than other methods that require heating larger areas to achieve treatment. The first RFH application for environmental remediation was performed in the early 1990s at an east coast naval shipyard. A number of RFH applications have been reported in literature over the years, including a successful RFH implementation to remove greater than 97% of 1,1,1-trichloroethane DNAPL in fractured bedrock (Kabir, 2010). However, because the literature and history on this technology is not as exhaustive as some of the other proven technologies, it is more difficult to evaluate the efficacy of this technology compared to the others. If considered, this would need to be pilot tested as an innovative technology. Based on a July 2018 internet research performed by CDM Smith staff, the only vendor offering radio-frequency heating services for environmental remediation applications is JR Technologies, LLC located in Great Barrington, Massachusetts. This research indicates however that JR Technologies, LLC has only completed one pilot-scale study investigating the effectiveness of RFH, and such study was conducted in 2003. No other application of the technology has been performed by JR Technologies, LLC for the last 15 years. Radio Frequency Co. (RFC) located in Millis, Massachusetts is the only other prominent Internet search result for RFH. However, RFC primarily focuses on industrial food/material processing and disinfection applications. CDM Smith's Internet research and phone conversation with RFC indicated that the company does not offer any remediation services. Overall, the research showed that the commercial availability and demonstrated field success of the RFH are extremely limited. Additional discussion on RFH will be provided in the CMS report, but the technology is not being seriously considered for Area IV remediation.

3.1.6 Hot Air Injection

Hot air injection is essentially a variation of steam injection (discussed in **Section 3.1.3**) that was developed by the petroleum industry to lower the viscosity of heavy oils, to increase the volatility of light oils, and to collectively enhance recovery of petroleum products. The technology involves injection of hot air/steam below the contaminated zone to promote heat-enhanced desorption and volatilization of VOCs. The conceptual design of a hot air injection system is graphically presented in **Figure 9**.

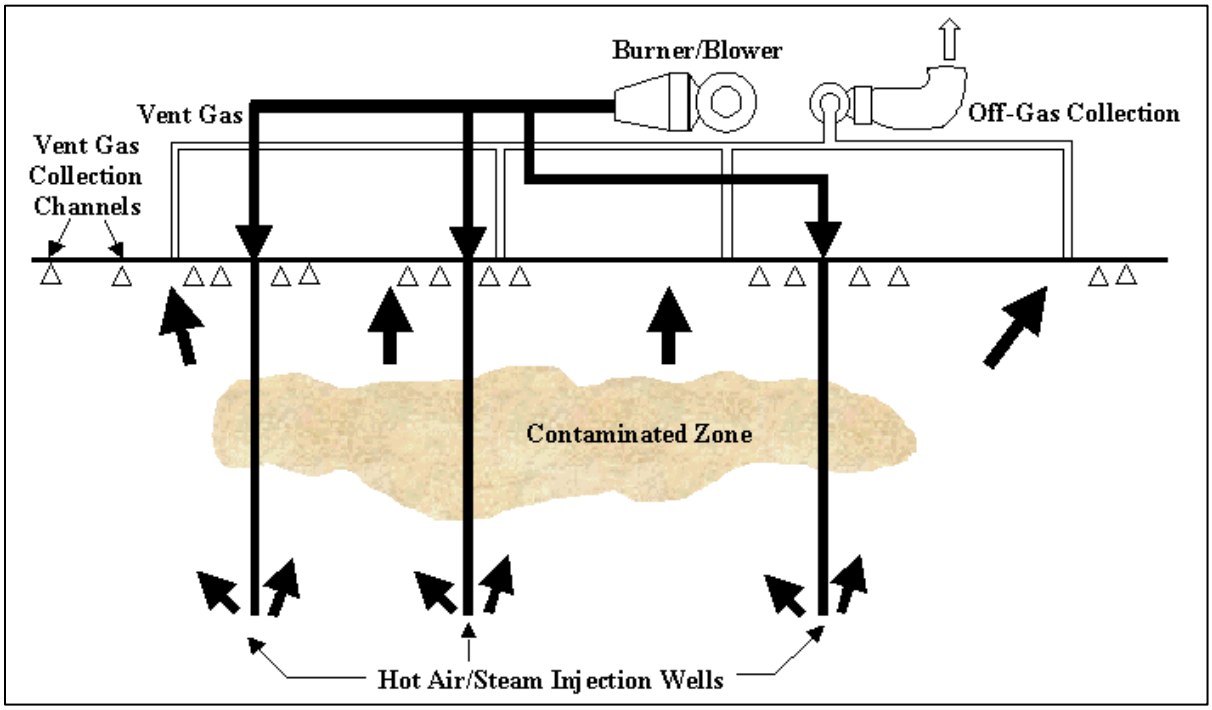


Figure 9. A Conceptual Design of a Hot Air Injection System (courtesy of ER-0314, 2010)

While it has been shown that hot air injection can conceptually facilitate recovery of a large percentage of volatile contaminants, residual mass often remains following implementation of this technique and other degradation mechanisms such as monitored natural attenuation (MNA) or bioremediation must be relied upon to further reduce contaminant mass. Laboratory studies have proven that hot air injection can successfully strip contaminants from the subsurface (Lingineni, 1992; Shah, 1995). However, application in the field is difficult, primarily due to the low heat capacity of air (1 kiloJoule/kilogram ˚C – approximately four times lower than steam). It is therefore difficult to maintain the subsurface temperature with air injection. Given the lack of its commercial availability and demonstrated success, hot air injection will be not considered as a potentially applicable *in situ* remedy at the Site for mass removal. But it is considered viable for potentially increasing biological activity and attenuation of contaminants.

3.1.7 Hot Water Injection

Hot water injection is another variation of the steam injection process (**Section 3.1.3**) that has been studied and, to a more limited extent, field-tested to aid in removal of NAPL from the subsurface. The primary difference between hot water injection and the other ISTR methods is that this is a liquid-only remediation technique, intended to mobilize NAPLs by decreasing their viscosity and interfacial tension. Because this method does not vaporize contaminants or heat up the subsurface to impact bedrock pore water, it will likely have limited effectiveness outside of

transmissive zones (i.e., bedrock fractures). Additionally, since this method does not aim to generate vapors, vapor recovery systems are generally not used and only liquid recovery systems are used. Because of this, a cold water "cover" is generally required to stop any vapors from releasing to the subsurface. However, this cold water "cover" will likely result in accumulation of vaporized contaminants with higher vapor pressures (i.e., benzene, TCE). While a number of hot water flooding studies have been conducted in the petroleum industry (Johnson, 1997; Johnson, 1990), limited work has been performed for remediation of contaminated subsurface with varying degrees of success. It is generally recommended for NAPLs with relatively low viscosities and lower densities, as hot water will rise through the water table after injected, and certain NAPLs will rise with the water if their density is decreased sufficiently with the increased temperatures. However, the elevated subsurface temperature could also have led to an *increase* in specific gravity of certain contaminants (i.e., density relative to water increases as water density decreases), which could result in contaminants migrating deeper into the aquifer. Therefore, hot water injection generally requires a competent aquitard beneath the treatment area to ensure downward mobilization does not occur. Given the incomplete understanding and the lack of commercial success of this technology, hot water injection is not considered viable for full-scale implementation at the Site and thus will not be further evaluated in this document.

3.1.8 Low-Temperature, Thermally-Enhanced Bioremediation

Traditional ISTR technologies rely on the heating of the subsurface, either via resistive or conductive energy transfer, to a temperature near or exceeding steaming/boiling point to promote volatilization, desorption, and/or destruction of contaminants. ISTR can be successfully applied at sites with differing lithologic and hydrogeological conditions, and can be effective for a wide range of contaminants. However, the capital and operating costs associated with ISTR can be very high when compared to other *in situ* treatment techniques. At sites where the remedial timeframe is not the primary driver, operating ISTR at a low energy input and only a modest temperature increases to promote biotic and abiotic degradation processes rather than the physical removal and/or destruction of the contaminants of concern in the subsurface may represent an attractive remedial alternative.

Low-temperature, thermally-enhanced remediation refers to the heating of the subsurface to approximately 60°C or less with electrical resistance heating to promote enhanced reaction kinetics in the subsurface via a number of physical, chemical, and microbiological processes. Compared to traditional ISTR, advantages associated with this low-temperature, thermally-enhanced remediation technique include the following:

- Due to the lower target temperature, energy inputs and equipment requirements are substantially less than for traditional ISTR. Power/current requirements are much lower, and because the focus of low temperature thermal remediation is to stimulate degradation reactions *in situ,* the amount of aboveground treatment equipment is significantly less. For some applications where no hydraulic control (and therefore no groundwater extraction) is required, it may not be needed at all.

- Microbiological reactions generally follow Arrhenius type behavior (e.g., reaction rates approximately double for every 10 degrees increase in temperature); reaction kinetics are expected to increase from temperatures typical of most groundwater systems (10-20°C) to reach a maximum at approximately 50°C then decline with further temperature increases. This relationship between reaction kinetics and subsurface temperature is well-

documented for general microbiological processes (Atlas and Bartha 1987 and Suyama et al 2002) as well as biological reductive dechlorination and abiotic dechlorination via zero-valent iron-aided beta elimination (Kohring et al 1989, Holliger 1993, He 2003).

- At sites with residual source material suspected or known to be present, application of low-temperature heating can facilitate enhanced mass transfer of residual DNAPL to the aqueous phase, thus making the contaminants available for microbiological, chemical, and/or physical reactions. Contaminant dissolution and volatilization rates generally increase with increasing subsurface temperature (Yaws et al. 2009, Sleep and Ma 1997, Horvath 1982). Imhoff et al, 1997 empirically and predicatively demonstrated that moderate temperature applications of hot water flushing for chlorinated solvent treatment can result in an increase of mass transfer rate of residual DNAPL by a factor of four to five when temperatures were increased by 5°C to 6°C. Therefore, combining moderate heating of the subsurface with a proven *in situ* treatment technique such as enhanced anaerobic bioremediation or *in situ* chemical reduction may eliminate the requirement for vapor recovery and treatment, which often represents a large fraction of ISTR implementation.

- Low-temperature heating of the subsurface also results in increased hydrolysis rates associated with chlorinated solvents, petroleum products, pesticides, and a number of energetic compounds. At sites where DNAPL is present, the increased degradation rates can increase the concentration gradient between the DNAPL and water interface (Yang 2000). This concentration gradient allows for more soluble degradation daughter products to be present in the aqueous phase and available for treatment (Carr 2000). Additionally, because relatively uniform heating of the subsurface can be achieved, degradation of these compounds can be stimulated in a variety of matrix types including sand, silt, clay, and bedrock if amendment distribution can be achieved.

- Elevated temperatures have been observed to also increase the hydrolysis rate of non-soluble humic and fulvic acids (e.g., organic carbon that is naturally occurring in aquifers), which can increase dissolved organic carbon levels by up to two orders of magnitude (SERDP 2014). Therefore, simply by heating the subsurface, additional electron donors required by subsurface microorganisms for microbial respiration and contamination transformation/destruction are fortuitously generated. Because non-soluble humic and fulvic acids are often well-distributed in the aquifer matrix, application of low-temperature heating may result in relatively uniform distribution of electron donors even in low-permeability zones; uniform delivery of electron donors in matrix with a high degree of heterogeneity often represents the one of the most challenging aspects of *in situ* remediation.

Low-temperature heating of the subsurface to aid *in situ* remediation has not been widely implemented in the field-scale setting. The two most prominent studies performed to-date utilizing this technology include a field research project funded by the Department of Defense's ESTCP entitled "*Combining Low-Energy Electrical Resistance Heating with Biotic and Abiotic Reactions for Treatment of Chlorinated Solvent DNAPL Source Areas*" and a pilot study funded by EPA Region 10 and entitled "*Applying Electrical Resistance Heating at Below Steaming Temperatures to Enhance Bioremediation Kinetics at the Well 12A Superfund Site*".

ESTCP project ER-200719 was intended to evaluate the use of low-temperature resistance heating coupled with Enhanced Anaerobic Bioremediation (EAB) and *in situ* chemical reduction (ISCR) to accelerate the dissolution, desorption, and degradation of residual TCE contamination. Electrical resistance heating was applied to both the EAB and ISCR test cells to increase the subsurface temperature to approximately 30°C to 45°C and 40°C to 55°C, respectively. The elevated temperatures increased the dissolution of contaminant into the groundwater and increased the rate and extent of dechlorination in both test cells. During this demonstration, the total contaminant mass discharge increased by a factor of 4-16 within the ISCR test cell, and consisted primarily of the reductive daughter products (ethene and ethane), as the degradation kinetics were sufficiently high to keep the TCE concentrations low. For the EAB test cell, the total contaminant mass discharge increased by a factor of approximately 4-5 and the fraction of the total mass present as ethene increased dramatically compared to baseline.

More recently, at the Well 12A Superfund Site, a pilot study was performed to evaluate the impacts of low-temperature, thermally-enhanced reductive dechlorination for treatment of chlorinated ethanes and chlorinated ethenes existing as DNAPL at two hot-spots where electron donor had previously been injected as a part of EAB activities at the site. Three heating electrodes with an anticipated heating radius of influence of approximately 10 feet and spanning the depth intervals of interest (approximately 40 to 50 feet below ground surface) were installed to aid subsurface heating from the ambient groundwater temperature of approximately 10°C up to 45°C. Groundwater monitoring and temperature measurements were performed periodically within each hotspot to facilitate system optimization and performance evaluation. Results show that VOC concentrations declined substantially since heating, and total VOC mass and molar concentrations have decreased by more than 99% from maximum concentrations observed immediately prior to heating and by 93% since baseline sampling in 2013. Substantial reductions have also been observed at a nearby monitoring well, with a greater than 98% decrease in molar concentration from the peak and 96% from baseline conditions. No significant contaminant mass removal has been observed at the other hotspot due to the presence of significant DNAPL mass.

Similar to traditional ISTR technology, the low-temperature, thermally-enhanced remediation technology is not limited by depth. However, given the Site's lithology and contaminant distribution, the cost associated with drilling and installation of deep electrodes may be significant. In addition, this technology has not been widely implemented with demonstrated success. Therefore, low-temperature, thermally-enhanced bioremediation will not be further evaluated in this document.

3.2 Summary of Thermal Treatment Technology Screening and Evaluation

Based on the commercial success and availability reported in contemporary literature, ERH and TCH alone, and/or in combination with SEE are anticipated to be the most applicable ISTR technologies for Site remediation. Overall, these techniques have been successfully implemented at many sites, and the industry has seen an increased number of applications in bedrock in recent years. Numerous laboratory studies and modeling exercises have also been performed to better understand the fundamental principles and to optimize these techniques in the field. State-of-the-practice and guidance documents are available for the design and implementation of ERH, TCH, and SEE. On the other hand, the other ISTR technologies such as vitrification and RFH are either very expensive, have only been demonstrated at few sites, and/or are still somewhat

experimental and are not widely commercially available. Therefore, only ERH, TCH, and SEE will be further evaluated for their applicability at the Site in this document.

Section 4

Site-Specific Discussion of Thermal Treatment Technologies

This section addresses the various technical challenges when implementing thermal treatment technologies at sites with unique lithologic, hydrogeological, and contaminant profile like SSFL. Specifically, common challenges in bedrock remediation, factors affecting selection of the appropriate thermal treatment technologies, and other engineering and management considerations are elaborated. In addition, the Site-specific applicability of the technologies is presented.

This section evaluates the thermal remediation technologies presented in **Section 3** in relation to techniques for implementation at the Site. Although in **Section 3** a variety of contaminant types and subsurface media were presented, this section includes a discussion of ISTR technologies based on SSFL conditions – specifically for TCE in fractured bedrock.

4.1 Challenges in Bedrock Remediation

Remediation of chlorinated solvents in fractured bedrock, especially when present as DNAPL, is a unique challenge because of at least four factors:

i. the difficulty in fully delineating the area requiring treatment,

ii. the potential impacts of matrix diffusion within and downgradient of the source zone,

iii. the discrete nature of fractured pathways, and

iv. the ability or lack thereof to access DNAPL within the fractures and contaminant mass within the matrix (Heron et al, 2008).

In fractured rock settings, a significant portion of the contaminant mass may exist diffused in matrix pore water, sorbed to mineral surfaces and organic matter, or as mobile or residual DNAPL. This condition does exist at the SSFL Site, as the majority of TCE remaining is present dissolved in the matrix pore water and very little is present in the actual fractures (Cherry, 2009). Although it is also reported that TCE DNAPL does not likely remain except as small, disconnected immobile globules, these small globules have the ability to act as long-term sources of elevated groundwater TCE concentrations at the Site. Many remedial technologies such as groundwater extraction, *in situ* bioremediation, or *in situ* chemical oxidation may only be effective at addressing some of these sources of contamination; matrix diffusion-driven transport of contaminants in and out of the contaminated matrix can render achieving satisfactory reduction in contaminant concentration using these technologies challenging.

ISTR is proven as an effective remediation technology for treatment of chlorinated solvents (including DNAPL) due to its ability to remove contaminants by multiple mechanisms including volatilization, enhancing their mobility and water solubility, increasing vapor pressures, and

decreasing viscosity, surface tension, and/or interfacial tension (Kingston, 2014). These mechanisms can result in enhanced mobility of all three contaminant phases (DNAPL, groundwater, and vapor) which allow for easier removal – generally via a vapor and/or groundwater extraction system. Additionally, ISTR has potential utility in fractured bedrock formations because it is capable of heating of the bedrock matrix and fractures, which results in subsequent enhanced mobility of contaminants from within the matrix pore water in addition to the fractures. While challenges do exist for removing contaminants from the bedrock matrix, ISTR has been successfully applied at several sites where contamination is present in bedrock. Other treatment mechanisms have been proven to contribute to contaminant mass destruction in association with some of the ISTR methods including enhanced bioremediation, hydrolysis, oxidation, and pyrolysis. However, enhanced mobility and extraction is the primary treatment mechanism (Heron, et al, 2008). It should be noted that while enhanced extraction followed by vapor recovery and treatment is also the primary mechanism for contaminant removal by SVE technology, there are several fundamental differences between the SVE and the ISTR technologies: 1) SVE can only be applied for treatment of vadose zone contamination whereas ISTR can be used to treat both the unsaturated and saturated zones, 2) SVE technology's effectiveness is highly dependent on site-specific lithology (i.e., SVE is most effective in removing volatile contaminants in permeable materials) whereas ISTR can be used to effectively remove contaminants from a variety of matrices with varying degrees of permeability, and 3) asymptotic rates of mass removal attributable to rate-limited mass transfer and thus diminishing returns are generally realized following several years of SVE operations whereas near complete and permanent contaminant removal is often achieved in ISTR implementation.

When ISTR systems are designed and operated properly, they prevent unwanted condensation of contaminated steam and vapors as they are recovered via a vapor extraction system. However, ISTR can be limited in its ability to extract contaminant mass from bedrock sites depending on the interconnectedness of the fracture network to the vapor and/or multiphase extraction wells and removal of mass within the rock matrix. Therefore, a robust understanding of the existing fractured network system directly in and immediately surrounding the target treatment zone is essential to implementing successful ISTR treatment in fractured bedrock.

4.2 Comparison of Factors Affecting Selection of Thermal Technologies

The major difference between thermal treatment technologies is their mode of energy delivery. The ultimate objective of increasing temperatures to enhance mobility of contaminants in the NAPL, vapor and/or dissolved phase where they can be extracted and treated, and/or destruction of contaminants in situ. The selection of one technique over another may be decided based on the temperature that needs to be achieved (only TCH allows temperature higher than 100°C), factors limiting energy distribution and delivery (lithology and hydrogeology), vendor availability, practical constraints (contaminant depth and distribution, energy requirements) and economic factors (ESTCP, 2009). A few of these factors are discussed herein with regard to the three main thermal treatment technologies that are likely most applicable at the Site: TCH, ERH, and SEE.

4.2.1 Contaminant Distribution

Because all of the ISTR technologies evaluated herein treat TCE effectively, comparisons will not be made for contaminant destruction mechanisms. While the primary remediation mechanism

for ISTR technologies is contaminant mobilization, removal, and above-ground treatment, some ISTR technologies can destroy contaminants in situ under certain conditions. The differences in how the various ISTR technologies remove and destroy contaminants will be addressed in the CMS. In terms of contaminant distribution, all ISTR technologies are best suited to NAPL source areas and high concentration zones. They have been documented to achieve large mass removals and significant concentration reductions when applied under these conditions. ISTR technologies are generally used to treat higher concentrations of contaminants because the subsurface heating costs are relatively independent of contaminant mass. The length of time the heating is implemented and ex-situ treatment are more likely to be affected by contaminant type and concentrations. Because of this, ISTR technologies are generally applied when appreciable NAPL is present, subsurface solid concentrations exceed 5-10 milligrams per kilogram (mg/kg), or groundwater concentrations exceed 1 mg/L. However, ISTR can be evaluated and implemented in areas where concentrations are lower than this. While technically feasible, ISTR may not be the most economical treatment option to address large and dilute downgradient plumes. Site-specific viability of such technology will be evaluated during the CMS.

4.2.2 Treatment Depth

The depth of treatment zones is only limited by the ability to deliver a heat source, such as steam, electricity or conductive heating, to the desired depth and the ability to recover the generated vapor/steam, NAPL and/or liquids to the surface. TCH, ERH and SEE have demonstrably remediated depths ranging from 11 to 110 feet bgs and treated material quantities ranging from 5,000 to 300,000 cubic yards. Deeper applications are possible and are constrained only by cost and feasibility of installing deeper wells and extraction infrastructure. ISTR technologies also allow for treatment to take place beneath existing structures or activity at the surface (USEPA, 2004).

4.2.2.1 Electrical Resistance Heating

Although it has never been attempted in bedrock at depths observed at SSFL (contaminants at <1,000 feet bgs), there would be expected technical and financial challenges in addressing contaminant depth and distribution for the application of ERH. The treatment zone can have any geometry or depth but site characteristics will affect the design of the heating and treatment systems. Shallow treatment zones will require insulating surface covers to manage heat losses, subsurface debris would influence drilling methods, and high permeability zones may require measures to control recharge into the treatment zone and associated heat losses. Implementation into very shallow zones (less than 30 feet) may have significant energy losses even with engineered controls applied.

4.2.2.2 Thermal Conduction Heating

Similarly, TCH theoretically could be applied at depths as deep as 1,000 feet (there are no examples of it being applied to depths greater than 100 feet bgs) and could experience heat losses at depths shallower than 10 m. As with TCH, these losses can be mitigated using engineering controls. In addition, ERH well spacing can be varied allowing the treatment zone boundary to be irregular and the depth interval to vary across the site. However, an eight-foot thickness is the thinnest region that can be practically treated with ERH without substantial heat losses.

4.2.2.3 Steam-Enhanced Extraction

Contaminant depth is an important factor for SEE application because shallow sites will not have sufficient overburden to achieve practical steam injection pressures. Application of SEE involves pressure of injected steam. As a rule-of-thumb injection pressure should not exceed 0.5 pound per square inch per foot of overburden. If paved or concrete surfaces are present this may allow SEE treatment to be practical at shallower sites. SEE is more effective for sites having contamination at greater depths below the surface, generally deeper than 3 to 6 feet (Department of Defense, 2006). Additionally, steam injection into very deep sites (> 1,000 feet) will require additional energy to keep the water above its boiling temperature at higher pressures.

4.2.3 Lithology and Hydrogeology

In terms of treating VOCs in the bedrock matrix, all three technologies have potential limitations. For TCH, heating up the bedrock uniformly will depend on the variation of lithologic material and the groundwater flux through the treatment area. For ERH, the availability of groundwater in the matrix itself will likely limit effective heating of the rock matrix. For SEE, because the steam follows the hydraulically transmissive pathways, this method is the least likely to treat VOCs diffused into the bedrock matrix but can work well to treat the contaminants present in fractures.

4.2.3.1 Electrical Resistance Heating

ERH is not sensitive to lithology in terms of achieving uniform heating, but heating rates for some aquifer matrices (including bedrock) might differ from others, and as with TCH, vapor recovery is influenced by variations in the type of material. Although in general all types of aquifer materials can typically be heated to the boiling point of water without difficulty, lithology becomes important at ERH sites to understand how NAPL would migrate and accumulate in the subsurface (Department of Defense, 2006). In some cases, electrical conductivity of the treatment zone may affect ERH performance (USEPA, 2014). Chlorinated organics and natural organic carbon in the bedrock will both result in higher electrical conductivities and provide more current density for enhanced ERH effectiveness. Therefore, ERH is preferred for the treatment of porous bedrock lithologies that have become consolidated within these zones having higher organic content (USEPA, 2004). Similar to TCH, vapor recovery is dependent on sufficient interconnectivity between the areas treated, and therefore it may not be possible to recover all of the contaminants depending on lithology.

ERH was used for successful treatment of TCE in a limestone/bedrock setting underneath an active industrial plant in Fort Worth, Texas (Fain, et al, 2002). Following 13 weeks of heating at 100°C, approximately 330 pounds of TCE were removed from the subsurface, resulting in 95% reduction of contaminant concentration in groundwater. ERH was recently applied in fractured sandstone bedrock (TRS Group, 2014). Because of low groundwater flux (this site was on a hill, similar to SSFL), high TCE concentration reductions were achieved, greater than 99% in bedrock after 82 days of operation. More details on this case study are provided in Section 4. In another fractured bedrock lithology, ERH was used in combination with excavation and biologically-mediated reductive dechlorination for approximately 98% DNAPL residual mass removal at a former manufacturing facility in Connecticut (Panciera, et al, 2012).

4.2.3.2 Thermal Conduction Heating

Out of all the ISTR technologies, TCH is the least sensitive to variations in soil/bedrock type because thermal conductivity varies only by a factor of ±3 for a wide range of materials. Both soils above and below the water table can be treated with TCH but measures to control the rate of water recharge and/or flow into the treatment zone are often necessary to achieve target temperatures. TCH is therefore more effective in low permeability lithologies - hydraulic conductivity less than 10^{-3} cm/s are generally acceptable for the application of TCH (Department of Defense, 2006). However, hydraulic control (or dewatering) methods are often used for TCH to be successful at sites with higher permeability. Vapor recovery is also influenced by variations in the type of soil and although bedrock sites can be heated by TCH, if there is not sufficient interconnectivity between the areas treated, it may not be possible to recover all of the contaminants.

Successful implementation of TCH has been reported at many different sites with lithologies including high-permeability loess, sand, and fill to low-permeability silt, clay, and fractured and competent bedrock. The first successful full-scale implementation of TCH for bedrock remediation was performed in 2007. At a fractured bedrock site located in the Southeastern U.S., TCH was used for subsurface heating to 100°C and approximately 90 feet bgs to facilitate treatment of TCE (Heron, et al, 2008). Following approximately 150 days of TCH operations, nearly 12,000 pounds of primarily TCE were removed from the subsurface. The implemented remedy resulted in reductions of TCE in groundwater within the treatment zone ranging between 75 and 99.7%. TCE soil concentrations were reduced to below the target remedial goal. More details regarding this field implementation are provided in **Section 4.2**. Other successful implementations of TCH for bedrock remediation have also been reported in recent literature (TerraTherm 2007a and 2007b, ESTCP 2012).

TCH performance in treating DNAPL in fractured mudstone bedrock was demonstrated in ESTCP project ER-200715 (ESTCP 2012). Sufficient heating was not achieved in all areas of the treatment area and only 41-69% decrease in TCE concentrations were observed within the target treatment zone. As discussed further in Section 4.3, this was primarily due to higher than expected groundwater flux into the target treatment zone through transmissive fractures. The groundwater moving into the treatment area acted an energy sink that resulted in lower than expected subsurface temperatures. In addition, because this demonstration was conducted in the center of a larger source area, the groundwater flowing into the treatment zone introduced significant concentrations of TCE. When excluding the TCE mass that started outside of the treatment zone, contaminant reductions were nearly 95%. Also, this demonstration showed that rock matrices with a combination of higher porosity and lower fraction of organic carbon exhibited higher degrees of contaminant removal. This suggests that the sandstone matrix present at the Site may be amenable to ISTR using TCH.

4.2.3.3 Steam-Enhanced Extraction

Because pressures must be applied to inject the steam, it may not be possible to treat at shallow depths unless a surface cover is present (e.g., Alameda Point, Pinellas STAR Center) or it is a fractured rock site with significant rock strength (e.g., Edwards AFB Site 61 [EarthTech and Steam Tech, 2003), Loring Quarry Site). Moderate to high permeability soils are preferable for SEE applications because lower permeability soils will require higher steam injection pressures

to penetrate pore spaces, which would result in higher steam temperatures and greater soil instability. The high injection pressure also limits contaminant mass transfer to the vapor phase. The lower limits of hydraulic conductivity for typical SEE applications are approximately 10^{-3} cm/s for sites less than 20 feet deep and approximately 10^{-5} cm/s for sites deeper than 30 feet (Department of Defense, 2006). Additionally, smaller pore diameters of treatment zone media create greater capillary pressures which also lowers the rate of evaporation of contaminants (USEPA, 2004).

However, low permeability soils can still be treated by combining SEE with ERH (as done at Pinellas STAR Center) or by injecting steam into adjacent higher permeability lenses and layers (Adams & Smith, 1998). Heterogeneities in lithology also influence the flow of injected steam in the subsurface because high permeability zones can cause preferential flow or channeling. However, channeling may be minimized because heat losses are also greater in these zones which results in slower flow within high permeability units and a more uniform steam front as a whole (USEPA, 2004). SEE has generally been applied for treatment at sites of high-permeability lithologies (Musterait, 2006, Larson, et al, 2002, and Jepsen et al, 2002) but has not been widely applied at low permeability bedrock sites. There are a limited number of SEE applications in fractured bedrock sites (Stephenson, 2006 and Nilsson, et al 2011). One reason is that SEE likely has a disadvantage compared to ERH and TCH since it will not heat into the bedrock matrix as effectively as the other ISTR methods. Since the majority of contaminant mass has been reported to be in the matrix porosity at the Site (Cherry, 2009), this will likely limit the effectiveness of SEE to treat the majority of TCE present in fractured bedrock at SSFL.

In summary, TCH, ERH and, to a more limited extent, SEE, have all been employed at fractured rock sites. TCH has been used in sedimentary and metamorphic rock including limestone, chalk, mudstone and gneiss. ERH and SEE have primarily been used in sedimentary rock such as sandstone and limestone (USEPA, 2014). Mixed results have been achieved, primarily due to the highly heterogeneous nature of fractured bedrock and to varying degrees of groundwater flux through the treatment zone. With the exception of the ESTCP demonstration, most of the case studies do not provide a rigorous analysis of contaminant mass removal in the bedrock matrix versus the fractures. Further details on ISTR case studies conducted at bedrock sites are provided in **Section 5.**

4.3 Other Considerations

This section presents other considerations that must be taken into account in selecting the appropriate thermal treatment technology at a site, including aboveground treatment requirements, hydraulic control requirements, generation of unwanted waste streams, and waste management. Details regarding these considerations are provided below with regard to the three main thermal treatment technologies that are likely most applicable at the Site (TCH, ERH, and SEE).

4.3.1 Aboveground Treatment Requirements

Because ISTR systems are designed to remove contaminants from the subsurface but are not intended to treat them *in situ*, an above-ground treatment system is required in ISTR systems. The conceptual design of the aboveground treatment system for a typical ISTR application is

graphically illustrated in **Figure 7**. Collected vapors are first processed through heat exchanger/condenser(s) and then a liquid-vapor separator(s) at which point they are separated into two treatment trains. The vapor-phase contaminants are treated (e.g. by introducing them into a vapor-phase carbon system) and then discharged to the atmosphere. Similarly, contaminants in the liquid phase are passed through an oil-water separator and a liquid-vapor separator. Aqueous phase effluent then enters water-phase treatment system such as activated carbon and subsequently discharged upon treatment, or at some sites it can be recirculated back into the thermal treatment zone. Any non-aqueous phase liquid effluent is stored for disposal. Other variations in the aboveground treatment system are often dictated by site-specific conditions such as the specific COCs present.

For TCE-contamination, granular activated carbon (GAC) is most commonly used for treatment of the vapor and liquid phases. When contaminant mass loading is high, thermal oxidation may be a more cost-effective choice than GAC. Vapor-phase contamination can be destroyed using a conventional thermal oxidation unit or a catalytic oxidation unit. Similar to conventional thermal oxidation units, catalytic oxidation system typically comprises a single reaction chamber, a propane- or natural gas-fired burner, and off-gas stack. Unlike conventional systems, catalytic oxidation units utilize a catalyst to accelerate the rate of oxidation and thus allow for efficient oxidation at much lower temperatures. Catalytic oxidation, however, may not be appropriate for treatment of halogenated compounds present in high concentration in the vapor phase because of the generation and accumulation of oxidation byproduct hydrochloric acid, which could foul the catalyst.

4.3.2 Hydraulic Control Requirements

Site-specific hydrogeology can significantly impact the heating regime of a thermal application. In ISTR applications, groundwater flow into the target treatment zone, such as what could occur through transmissive fracture zones, can lead to cooling of the thermal treatment zone, which must be limited by means of a hydraulic or physical barrier or overcome by injections of steam into highly conductive zones. Taking into account the flow of cool groundwater into the target thermal treatment zone was among one of the most important lessons learned during the ESTCP demonstration project ER-200715 (ESTCP, 2012). Installing additional ISTR wells may also be considered to overcome the adverse effects of cooling caused by high groundwater flow. In some cases, a groundwater flow model and/or even a 3-dimensional visualization may be warranted at sites of complex hydrogeology to facilitate informed decisions on hydraulic control requirements. Similar to TCH, hydraulic control is required for applications of ERH at sites with high groundwater flow. At the groundwater velocities greater than 1 foot per day, significant heat loss may occur and hydraulic controls must be considered. In applications of SEE in the vadose zone, hydraulic control must be considered to ensure recovery of contaminant-rich condensates that are generated in the formation during the cooling phase of SEE operations.

4.3.3 Waste Management

Application of heat to the subsurface at sites with high contaminant mass loading should result in increased contaminant mobility and concentrations. As a result, NAPL may be recovered as a waste stream and must be handled appropriately. Offsite disposal of spent GAC and recovered NAPL must be performed in accordance with all local, state, and federal regulations. With the exception of volatile metals such as mercury, thermal technologies including TCH, ERH, and SEE

are not capable of remediating inorganic contaminants. Although heat-enhanced mobilization of inorganic contaminants including metals and radionuclides may occur, it has not been reported in contemporary literature. Although it is not anticipated, any waste mixed with radiological contamination must be disposed of properly. Any radiological mixed waste generated will result in significant cost increases.

4.3.4 Miscellaneous Considerations

Other components that must be considered during the design and implementation of ISTR include the following:

- Surface cover: at sites where vapor migration is of concern, construction of an impermeable cap should be considered on the surface of the treatment area. While existing pavement may suffice, concrete, asphalt or a temperature- and contaminant-resistant geomembrane are suitable and effective materials for sealing. The surface cover can provide protection against water infiltration and increase the radius of influence of the vapor recovery wells.
- Modeling: the use of mathematical models to predict physical and chemical processes that are important in ISTR implementations has been frequently demonstrated in contemporary literature (US Army Corp of Engineers, 2014). Many thermal vendors now rely on modeling to aid heater well spacing design, facilitate design and sizing of hydraulic control and aboveground treatment systems, predict heating duration and contaminant removal, and estimate energy requirements.

4.4 SSFL Site-Specific Applicability of Thermal Technologies

This section provides a summary of the efficacy of the three thermal technologies that are likely most applicable at the Site given the lithologic and hydrogeological challenges present at SSFL. It should be noted that, of the three main thermal technologies discussed earlier, only ERH and TCH have been demonstrated to be capable of treating TCE in fractured bedrock lithologies. Both have been successfully applied to different fractured bedrock types including sandstone. Similarly, the use of SEE as a standalone *in situ* technology for bedrock remediation has not been reported as frequently. This is because the primary governing mechanism for heating in SEE is through transmissive zones, which is often very low in bedrock matrices. Therefore, SEE is believed to be more applicable in high-permeability lithologies such as sand, silt, gravel, and highly weathered bedrock (Heron 2010). However, SEE may be used in combination with ERH and TCH in select ISTR applications for enhanced contaminant mobilization and recovery. Another application that one of the TCH vendors is now considering is to use SEE to treat highly transmissive fractures at TCH sites (ESTCP, 2012).

The two primary factors that appear to affect performance of ERH or TCH in fractured bedrock and therefore its potential applicability at the Site include:

- A robust understanding of contaminant distribution and phase the contaminants that are present in the subsurface. As discussed above in **Section 4.1**, the effectiveness of ISTR will rely greatly on understanding the various compartments where contaminant mass can be stored in a fractured rock setting (e.g., sorbed, diffused into the matrix, high flow fractures, etc.). ISTR can be effectively implemented to remove the VOCs present at the Site, but

characterization of the target treatment area will be critical in terms of understanding in what phase the contaminant mass is present, as well as whether it is stored in the matrix or is present in discrete fractures. Also, the type of rock present at a site can impact ISTR effectiveness in that higher porosity matrices may allow for better removal that dense, low porosity rock, simply because extraction is easier. The current understanding of the Site states that little contaminant mass remains in fractures, and that groundwater contamination at the Site is present in a sandstone matrix. These factors together suggest that ISTR may be applicable.

- The detailed understanding of the groundwater flow regime in and immediately surrounding the target treatment zone. This includes the ability to understand groundwater flow conditions and to potentially control the hydraulic gradient under conditions of ISTR operation. Although the Site-wide SCM (Cherry, 2009) indicates that the groundwater flow as well as the fate and transport of TCE is well understood at this Site, there will likely be treatment-area specific details that need to be understood before applying ISTR technology. Once target treatment zones for ISTR are defined, it will be critical to develop a detailed understanding of groundwater hydraulics to ensure proper heating will occur in the treatment zone is essential to effective ISTR treatment. This likely will entail inclusion of some type of hydraulic control to limit groundwater flow into the treatment zone.

While ERH and TCH have generally been used for sites with treatment zones of less than 120 feet, nothing inherent to these technologies would preclude implementing them at deeper locations. The underground and aboveground system components can be designed and implemented to overcome issues associated with heat loss or incomplete vapor recovery. Therefore, both ERH and TCH, combined with SEE as appropriate, may be potentially applicable for treatment of TCE in bedrock at depths greater than 100 feet bgs at the Site. None-the-less, considerations must be given to the feasibility and cost associated with installing the required number of wells, borings, etc., for an ISTR system in these settings. It should be noted that while successful ISTR treatment of fractured bedrock has been reported in contemporary literature, remediation of contaminated competent bedrock, which has been encountered in some areas of the Site, using this technology has not been documented. Detailed analysis of the applicability of ISTR at different areas of interest at the Site will be performed as part of the CMS.

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Section 5
Case Studies

This section presents case studies where thermal remediation was applied for treatment of chlorinated solvents in a bedrock lithology. First, the methodology used to research the case studies is described, and then example case studies are presented that highlight applications of ERH and TCH for remediation of VOCs in fractured rock.

5.1 Research Methodology and Results

The evaluation of the practice of "state-of-the-practice" thermal technologies started with a comprehensive literature review intended to capture the fundamental principles, laboratory experimental studies, modeling exercises, optimization studies, and field implementations of the technology. Results from this search, which include numerous peer-reviewed journal articles, conference proceedings, and book chapters, were subsequently screened to refine the results such that they were focused on case studies applicable to conditions that are present at the Site. In addition, case studies from the most prominent thermal technology vendors were obtained. The complete list of literature obtained for this evaluation is presented in Appendix A; the documents/reports that are publicly available are also provided.

Subsequently, each relevant literature research result was recorded in a database with information about the type of publication, authorship, information about the site, as well as a summary of performance of the thermal remediation implemented. A summary of the literature database is as follows:

- The literature database consists of 180 entries, of which more than 50 are peer-reviewed journal articles and 75 are case studies of field implementation. Also included were proceedings from national and international conferences, book chapters, project reports, and academic theses. The year of publication of these resources range from 1995 and 2015.
- Literature focusing on the field implementation of thermal technologies comprises the majority of the database. Several resources were state-of-the-practice reports relevant to applications of thermal remediation technologies in the field of environmental engineering. The remainder primarily consists of laboratory studies, modeling exercises, and life cycle and material flow analyses.
- As to be expected, the majority of the literature results focus on ERH or TCH. It should be noted that, in many cases, these technologies were employed in combination with other remedial technologies such as multi-phase extraction, steam-enhanced extraction, in situ bioremediation, and in situ chemical reduction.
- In the majority of the database entries (more than 110), the COCs are chlorinated solvents including chlorinated ethenes and ethanes; COCs in the remaining entries include

petroleum and polycyclic aromatic hydrocarbons (PAHs), jet fuels, heavy metals, and radionuclides.

- The treatment depths reported range between approximately 10 to 160 feet bgs. Target/achievable subsurface temperatures range between 25 °C for some thermally-enhanced bioremediation applications to approximately 70 to 100°C for the majority of electrical resistive heating and thermal conductive heating applications.

Of the collection of resources located during the literature review, thirteen results were found associated with applications of thermal remediation technologies at fractured and competent bedrock sites. Some of the different bedrock lithologies encountered include fractured limestone, competent shale, fractured sandstone, and saprolite. Most of these applications were ISTR projects conducted in overburden and underlying bedrock simultaneously; however, few were conducted exclusively targeting bedrock.

Because the focus of this document is to discuss applications of thermal remediation under conditions applicable to the Site, a summary of these case studies is presented in **Table 1**. This table shows information about each site, including location, depth, type of bedrock, as well as the thermal remediation technology that was used. A summary of the results is also provided. From Table 1, it can be seen that the contaminant mass removed varied widely at these sites, but this is of course dependent on the mass that was released to the subsurface and the scale of the thermal remediation application. Importantly, for the case studies where it was assessed, percent reduction in soil and/or groundwater concentrations were all very high (>90% in most cases).

The following sections present more details on selected case studies from Table 1. The case studies described below are considered to be the most representative to the Site of those included in Table 1.

Table 1 Case Studies of ISTR in Fractured Bedrock

Study	Authors	Year	Site	Thermal Technology	Lithology	Max Treatment Depth (feet)	COCs	Mass Removal	Contaminant Concentrations
Use of Thermal Conduction Heating for the Remediation of DNAPL in Fractured Bedrock	Heron, G., et al., 2008	2008	Confidential industrial fractured rock site, Southeastern US	Thermal conductive heating	Fractured bedrock	90	TCE	12,000 lbs removed	Pre-treatment: 81,000,000 µg/kg TCE soil and 1,100,000 µg /L groundwater; Post-treatment soil 17 ug/kg and groundwater <5 µg /L
Dense Non Aqueous Phase Liquid (DNAPL) Removal from Fractured Rock Using Thermal Conductive Heating (TCH).	ESTCP, 2012	2012	Naval Air Warfare Center West Trenton, NJ	Thermal conductive heating	Siltstone / Mudstone fractured bedrock	54	cVOCs	Approximately 530-680 lbs of TCE were removed in 3.5 months of operation. Rock chip concentrations were reduced by 41-69% on average in the rock samples close to fractures where cooling influence hindered complete heating; 94.5% removal accomplished in the samples where target temperatures were achieved. Groundwater concentrations not monitored during this study.	
TeCA Remediation using ERH in Soil, Fractured Rock and Groundwater, U.S. Naval Station Annapolis, Maryland	TRS Group2008.	NA	US Naval Academy in Annapolis, Maryland	Electrical resistance heating	Hard layer of sand, iron over fractured sandstone	70	TeCA and TCE	99.9% reduction in soil	Pre-treatment: 23,794 µg/kg total CVOCs Post-treatment: 50% non-detect, remaining average 31 µg/kg total CVOCs
TCE Remediation in Deep Bedrock, Eastern Pennsylvania	TRS Group,	2014	Confidential site in eastern Pennsylvania	Electrical resistance heating	Overburden from surface to 20 ft bgs. Sandstone bedrock from 20-ft to 110 ft-bgs	110	cVOCs	> 99% reduction in overburden and bedrock	Pre-treatment: 560,000 µg /kg TCE rock and 46,000 ug/L groundwater; Post Treatment < 50 ug/L groundwater (rock not assessed) Post-treatment: < 400 µg /kg TCE

Table 1 Case Studies of ISTR in Fractured Bedrock

Study	Authors	Year	Site	Thermal Technology	Lithology	Max Treatment Depth (feet)	COCs	Mass Removal	Contaminant Concentrations
Hydraulic characterization for steam enhanced remediation conducted in fractured rock	Stephenson, K. M., 2006,	2006	Loring Air Force Base in Northern Maine	Steam enhanced extraction	Fractured limestone	95	VOCs (mainly PCE)	> 16.3 lbs removed	
Guaranteed Fixed Price Remediation of TCE, PCE and VC in Soil and Bedrock under an Active Manufacturing Facility Confidential Client: Greensburg, IN	TRS Group	2009	Active manufacturing facility, Greensburg, IN	Electrical resistance heating	Clay and sand overlying dolomite bedrock	38	TCE, PCE and VC	95% UCL of 13 mg/kg for TCE and 1 mg/kg for VC, and 23.8 mg/kg PCE in soil	
Performance of a Large-Scale Combined Bioremediation and In Situ Thermal Treatment Project to Remediate CVOCs and DNAPL	Panciera, M., et al, 2012	2012	Former manufacturing facility in CT	Electrical resistance heating + Bioremediation	Till and weathered bedrock	40	TCE	600 lbs of TCE and ~ 98% of residual mass removed	Pretreatment: CVOC concentrations up to 780,000 µg/L in source zone groundwater and over 20,000 µg/L in resulting downgradient GW plume
Source Area Remediation of PCE in Soil: Fair Lawn, New Jersey	TRS Group	2008	Former Topps Dry Cleaners property, Fair Lawn, NJ	Electrical resistance heating	Glacial till overlying fractured sandstone bedrock	26	PCE	99.9% and 98% reduction in soil and GW, respectively	Pretreatment: 288,000 µg/kg maximum, 31,000 µg/kg average PCE in soil Post-treatment: < 100 µg/kg
Guaranteed Remediation of TCE, TCA and Freon 113 Confidential Client – Upstate New York	TRS Group	2015	Former storage yard in south central New York	Electrical resistance heating	Sand, clay, gravel, till, shale bedrock	28	TCE, TCA, and Freon 113	99.99% reduction for all COCs	Pre-treatment: 826,000 µg/kg maximum CVOC Post-treatment: < 470 µg/kg TCE, < 680 µg/kg TCS, < 6000 µg/kg Freon 113

Table 1 Case Studies of ISTR in Fractured Bedrock

Study	Authors	Year	Site	Thermal Technology	Lithology	Max Treatment Depth (feet)	COCs	Mass Removal	Contaminant Concentrations
Remediation of TCE NAPL in Active Alleyway, Arlington, Texas	TRS Group	2012	Narrow alleyway between buildings in Arlington, TX	Electrical resistance heating	Clay and silty clay overlying shale	32.5	TCE and Freon 113	95.5 and 99.9% reduction in TCE and Freon 113, respectively	Pre-treatment: 83,000 µg/kg TCE and 52,000 µg/kg Freon 113 in soil Post-treatment: < 10,000 µg/kg TCE and 50 µg/kg Freon 113 in soil
Remediation of Trichloroethene using Electrical Resistance Heating at an Operating Industrial Manufacturing Facility Confidential Client, Springfield, MO	TRS Group	2012	Former industrial manufacturing facility, Springfield, MO	Electrical resistance heating	Residual clay with variable limestone and chert floaters and limestone pinnacles	65	cVOCs	> 99% reduction in for all COCs	Pre-treatment: 116,000,000 µg/kg TCE, 1,350,000 µg/kg 1,1-DCE and 126,000,000 µg/kg 1,1,1-TCA Post-treatment: < 400 µg/kg TCE
Removing CVOCs Under a Building Equals Increased Property Value, Tucker, Georgia	TRS Group	NA	Manufacturing building, Tucker, GA	Electrical resistance heating	Weathered bedrock	19	cVOCs	99.98% reduction in cVOCs	Post-treatment: 2.6 µg/kg PCE, 4.1 µg/kg MeCl, 2.5 µg/kg TCE, and 2.2 µg/kg DCE
ERH in Soil and Groundwater U.S. Army - Redstone Arsenal Alabama	TRS Group	2015	Redstone Arsenal near Huntsville, Alabama	Electrical resistance heating	Silt and clay overburden with Karst limestone bedrock	68	TCE	> 90% reduction in GW > 89% reduction in soil	Pre-treatment: 1,850,000 µg/kg average in soil Post-treatment: < 5000 µg/kg

case study summarized in **Section 5**

5.2 Use of Thermal Conduction Heating for the Remediation of DNAPL in Fractured Bedrock

This case study presents the first full-scale remediation of DNAPL at a fractured bedrock site using TCH (Heron et al, 2008). The confidential site is located in the southeastern part of the U.S. with a TCE DNAPL source zone extending to approximately 90 feet below ground surface. Four major geologic units were present at the site including (1) approximately 25 feet of fill, (2) 30 feet of severely weathered granitic gneiss (saprolite), (3) 20 feet of partially weathered granite bedrock, and (4) fractured granite bedrock at depth between 70 and 80 feet bgs.

Groundwater is encountered at this site at the bottom of the saprolite layer at approximately 55 feet bgs. The primary COC at the site is TCE, which was released via a sump/catch basin associated with an aboveground TCE storage tank and a TCE reclamation unit. The target treatment zone encompassed an area of approximately 33 feet by 76 feet along the axis where highest TCE concentrations in groundwater were encountered. While the target treatment depth was 87 feet, the heater interval extended to approximately 90 feet to ensure uniform heating at the bottom of the treatment zone.

The TCH system was designed to achieve a remedial standard of 60 micrograms per kilogram (µg/kg) of TCE in soil of both the saturated and unsaturated zones. A targeted temperature of 100˚C was selected based on numerical simulations performed during the system design. Several noteworthy design components were included for this project including installation of a patented "hot floor" barrier, a low-flow groundwater extraction system to prevent downward migration of DNAPL, and perimeter heater-vacuum wells to contain vapors within the treatment zone. Specifically, heaters were installed into the upper 10 to 15 feet of the bedrock and increased power outputs were delivered into these wells to establish a "hot floor" barrier to mitigate vertical migration. In addition, a low-flow groundwater extraction system was implemented to slightly lower the water table within the treatment zone, resulting in an upward hydraulic gradient across the bottom of the treatment zone. This was designed to offset any downward forces acting on the DNAPL and to prevent downward migration of contaminants. Several heater-vacuum wells were installed at the boundary of the treatment zone to prevent inadvertent pushing of contaminants offsite. A total of 24 heater wells/borings were installed, ten of which were also used for vapor extraction. Seven temperature monitoring points with vertical array of thermocouples were installed between the thermal wells to facilitate performance evaluation of the thermal system at different geologic units. The aboveground treatment system includes a vapor collection system consisting of a vapor/liquid separator and a vacuum blower; fiberglass manifold piping system; and a liquid condensate pipe that was connected to the existing groundwater treatment at the host facility.

The target temperature was attained throughout the entire treatment zone within 100 days of system operation. Soil confirmation sampling was performed following 110 days of heating. Results based on 56 discrete soil samples showed significant contaminant mass removal in soils of both the saturated and unsaturated zones. Pre-remediation TCE concentrations in soil and groundwater were as high as 81,000,000 µg/kg and 1,100,000 µg/L, respectively. Post-remediation 95% UCL of the mean TCE soil concentration for the entire treatment zone was 17 µg/kg while groundwater concentrations were reduced to below 5 µg/L. The total mass of VOCs

removed from the subsurface during TCH implementation was approximately 12,000 lbs. A detailed breakdown of mass removal in each of the four major geologic units was not conducted. However, samples were collected from all four units as a part of the post-remediation assessment, so it can be inferred that reductions were achieved throughout all of the geologies. However, an analysis of the extent of removal in weathered/fractured bedrock versus competent bedrock is a data gap from this application. That being said, as the first TCH application in bedrock, this project demonstrated that TCH can be an effective remedial option for heating and treating contaminated fractured bedrock.

5.3 TCE Remediation via ESTCP Technology Demonstration in Fractured Bedrock at the Naval Air Warfare Center

A TCH demonstration was conducted at the Naval Air Warfare Center (NAWC) in Trenton, NJ, and the results summarized below are fully described in ESTCP, 2012. The objectives of the project were to demonstrate the feasibility of TCH to heat the target volume of rock and water, to evaluate the degree of heating at various distances from heater wells, to assess the impact of the cooling influence of inflowing water, and to assess contaminant removal from the rock matrix and fractures.

The conceptual model for the site was that TCE mass is held tightly in the rock matrix, and potentially in some of the fractures at the site. The TCE has dissolved, diffused, and adsorbed to the rock matrix (silt and mudstones). The VOC plume in the field demonstration area consists of TCE and its degradation products c-DCE and VC. Water samples from wells located less than 50 ft from the TCH field demonstration site have exhibited TCE concentrations that ranged from 5,000 to 60,000 μg/L, c-DCE concentrations from 10,000 to 25,000 μg/L, and VC concentrations from 500 to 2,000 μg/L. Laboratory treatability studies, modeling studies of thermal remediation, and a field demonstration were conducted as a part of this project.

For the field demonstration, 15 TCH heater borings and 15 co-located vapor extraction points were installed, along with 8 temperature monitoring points, all within an area with a diameter of approximately 20 ft. The boreholes at the site were installed as close as 1.2 ft apart, with heater wells being as close as 5 ft (in contrast, for a normal full-scale TCH operation, heater well spacing is 12-15 ft). TCH operations ran continuously for 106 days; the heating period lasted a total of 97 days, while the extraction system operated for 106 days.

Samples were collected from the bedrock before and after treatment, and extensive process monitoring was conducted throughout the field demonstration. Results from the bedrock samples indicate that the average reduction in TCE concentrations was 41-69%. However, careful examination of selected points in the rock matrix revealed that the rock matrix did not achieve targeted temperature in all locations (due mostly to contaminated groundwater influx through existing fractures). Since discrete sampling was done at 5 feet intervals, it was possible to identify at which depth there was incomplete heating and correlate that with observed fractures from a video log of the boreholes. Elimination of data the points where boiling water temperature was not achieved due to cool water influx, the average reduction was higher at 94.5%. During the cooling period, the zones that were slow to heat did not cool rapidly, indicating that regional groundwater flow was not dominant in controlling the cooling. This means that the elevated

flows during treatment were caused by the extraction system, which significantly increased flowrates during ISTR operations.

The data also shows that most rock concentrations were lowered to 0-5 mg/kg, but that higher concentrations were maintained at distinct depth intervals. These depths correlated reasonably well with the depth showing the highest TCE concentrations prior to heating. A total (vapor and liquid) of approximately 530 lbs based on daily PID readings and approximately 680 lbs based on analytical data of TCE was extracted from the site.

Overall, key lessons learned from this demonstration project include:

- flow into the treatment zone must be understood and controlled;
- for sedimentary rock formations, TCH can reduce matrix concentrations of TCE;
- Samples of sandstone and dolostone with a combination of higher porosity and lower fraction organic carbon exhibited higher degrees of contaminant mass removal than other rock matrices; and
- Heating duration had a greater effect on the degree of TCE and tetrachloroethylene (PCE) mass removal compared to heating temperature (i.e., higher temperatures did not accelerate removal).

5.4 TeCA Remediation Using Electrical Resistance Heating in Soil, Fractured Rock, and Groundwater

In this case study, ERH was employed for source area treatment of 1,1,2,2-tetrachloroethane (TeCA) and TCE at the U.S. Naval Academy in Annapolis, Maryland (TRS Group, 2008). Site lithology consists of a very hard layer of dense sand and iron extending to approximately 40 feet bgs and overlying fractured sandstone. Groundwater is encountered at approximately 60 feet bgs. A total of 24 electrodes with co-located vapor recovery wells were installed to encompass the target treatment area of approximately 8,500 square feet. The target heating interval ranging between approximately 30 and 70 feet, representing treatment approximately 10 ft into bedrock. Five temperature monitoring points, each of which contained between 9 and 15 thermocouples that were vertically spaced between 5 to 75 feet bgs, were installed within the treatment zone to allow for performance monitoring.

Approximately 2,000 pounds of chlorinated volatile organic compounds (cVOCs) were recovered following 100 days of ERH operations. Confirmation soil sampling was performed one year following the interim soil sampling and termination of the ERH system. VOCs were not detected in half of the soil confirmation samples and the average reduction in total CVOC concentration was 99.9%. As with some of the other case studies, a detailed breakdown of mass removal in the bedrock matrix, fractures, and the overburden was not conducted. However, samples were collected from both units as a part of the post-remediation assessment, so it can be inferred that reductions were achieved throughout both geologies. The project demonstrated the efficacy of ERH in treating chlorinated solvents at a site where contamination is present in fractured bedrock lithology.

5.5 Electrical Resistance Heating Remediation in 90-Foot Rock Formation

ERH was used to remove chlorinated solvents from a 90-foot-thick sedimentary rock sequence at a confidential manufacturing facility site in eastern Pennsylvania (TRS Group, 2014). The site had 20 ft of overburden; perched groundwater was encountered at 17 feet bgs, just above the bedrock, which was present from 20-110 ft bgs. Maximum concentrations of TCE in soil and groundwater were 560 mg/kg and 46,000 µg/L, respectively. TCE and cis 1,2-DCE were the primary contaminants of concern, however, other CVOCs were present at insignificant concentrations. The system was designed to remove contaminants from the overburden, which consisted of medium to fine sand and clay, and 90 feet of rock consisting of sandstone with some siltstone and thin seams of coal. The treatment zone was 2,800 square feet in size with treatment depth ranging from 4 to 110 feet bgs, leading to a total treatment volume of 11,100 cubic yards. The remedial goal was to remove as much of the estimated 483 lbs of TCE present in the subsurface as possible.

The treatment system consisted of 17 vertical electrodes with co-located vapor recovery wells and three temperature monitoring points, spaced at 5-foot depth intervals. Vapor stream sampling results were monitored continuously and operation was ceased after approximately three months when asymptotic CVOC concentrations in the vapor stream were reached. Based on the monitoring of the vapor stream, a total removal of 399 lbs of TCE and DCE combined was achieved. Analytical results from two groundwater well samples before and after ERH application demonstrated a 99.9% reduction of TCE concentrations in the shallow well and a 99% reduction in the deep well. While a detailed post-remediation rock coring/sampling program was not implemented at this site, based on the pre-remediation mass estimate of 483 lbs, approximately 83% of the mass was removed. As with other case studies, a detailed assessment of mass removal from the matrix versus fractures was not conducted as a part of this project. However, this case study discusses the first time ERH was used to treat a thick rock unit.

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Section 6
Cost Estimation

Cost information associated with field implementation of TCH and ERH – the two thermal remediation technologies that are likely most applicable for Site remediation – was not available for all literature items reviewed. However, the reported cost information indicated that the treatment unit cost associated with ERH ranges between $70 and $130 per cubic yard of treated materials. Reported treatment unit costs for TCH range between $79 and $650 per cubic yard. It should be noted that the upper end of the TCH treatment unit cost was associated with a full-scale treatment of PAHs, pentachlorophenols, and dioxins where a temperature that is much higher than that typically required for thermal treatment of chlorinated solvents was used. Also, it should be noted that an independent consultant is often involved in the design, implementation, and post-treatment confirmation sampling phases of an ISTR project. Costs associated with these activities are often not accounted for in the vendor-provided treatment unit costs. Therefore, the treatment unit costs presented herein are likely biased low, even when considered for shallow, unconsolidated sites.

As further example, McDade (2005) studied costs for common source area remediation technologies. They found that ISTR project costs ranged from $32 to $300 per cubic yard (ERH and TCH sites were grouped together for this study.) ESTCP (2012) conducted a cost analysis for scale-up of TCH to a range of scales of sites, and they estimated costs to range from $91 to $269 per cubic yard. It should be noted that expanding the areal extent of the ISTR footprint has a much large impact on cost than extending deeper into the subsurface for a given areal footprint.

Similar to other remedial technologies, the treatment unit costs associated with thermal technologies such as ERH and TCH are subject to the economies of scale and a host of site-specific factors. Because of the high costs associated with the mobilization of thermal vendor-provided treatment equipment, treatment unit costs for thermal remediation decrease significantly as the quantities of contaminated materials requiring treatment increase. Thermal remediation is ideal for projects involving treatment of large quantities of waste in small volumes of contaminated media.

The types of contaminants present, their physical and chemical characteristics, and their extent and distribution in the subsurface can individually and collectively impact the thermal treatment unit cost. For example, the lower the contaminant volatility, the higher temperature and likely longer treatment duration are required. Higher temperature requirements result in higher energy inputs and thus higher operating costs. Because operating costs including labor and energy are directly related to operational duration, the longer the heating time is, the more expensive the total project cost and treatment unit cost are.

In addition, the deeper the target treatment depth, the higher the costs for drilling and installation of *in situ* thermal equipment. Other site-specific factors including power and/or fuel availability, hydrogeology, and protection of onsite utility can also impact the thermal treatment unit cost. For example, if power is not readily available at a site, the costs for providing the

necessary power requirements for thermal application may drastically increase the project total costs. The need for hydraulic or pneumatic controls to overcome site-specific hydrogeological issues or other engineered means for protection of onsite utilities or downgradient receptors may also result in an increase in project cost, as the amount of groundwater and vapor recovery has a direct impact on treatment system sizing. As noted above, increased contaminant loading and specific contaminants can also require more robust or varied treatment equipment.

Regulatory-driven thermal treatment goals can also impact the project treatment unit cost. For example, stringent cleanup goals may result in longer heating duration, higher electricity usage, and thus higher project costs. In addition, the level of required monitoring for the aboveground treatment system may also impact costs. For example, vapor and liquid treatments systems with elaborate ambient monitoring equipment must be constructed for projects with stringent air and water discharge requirements.

With regard to the thermal application utilizing either ERH or TCH at the Site, given the aerial and vertical extent of contaminant, the primary cost drivers are likely associated with drilling and installation of *in situ* thermal equipment. Detailed cost estimates will be created during the formal development of an ISTR alternative during the future Corrective Measures Study.

Section 7
Conclusions

The review of successful thermal treatment actions identified three primary ISTR technologies with potential applicability at SSFL: TCH, ERH, and SEE. Of these, TCH and ERH have been applied most frequently in bedrock, as the comprehensive literature review revealed that fourteen ISTR applications in bedrock have been reported to date. These technologies are best equipped to mitigate the challenges presented by highly heterogeneous subsurface that are present at bedrock sites compared to other ISTR technologies. In addition, both TCH and ERH are applicable for remediation of chlorinated solvents, as dozens of applications have been reported over the past two decades.

Applications of these technologies at the depths that would be required in some areas of SSFL have never been attempted. Two of the primary factors that would be expected to affect performance of ERH or TCH at the Site include:

- A robust understanding of contaminant distribution and phase the contaminants are present in the subsurface. As discussed above in Section 4.1, the effectiveness of ISTR will rely greatly on understanding the various compartments where contaminant mass can be stored in a fractured rock setting (e.g., sorbed, diffused into the matrix, high flow fractures, etc.). ISTR can be effectively implemented to remove the VOCs present at the Site, but characterization of the target treatment area will be critical in terms of understanding in what phase the contaminant mass is present, as well as whether it is stored in the matrix or is present in discrete fractures. Also, the type of rock present at a site can impact ISTR effectiveness in that higher porosity matrices may allow for better removal that dense, low porosity rock, simply because extraction is easier. The current understanding of the Site states that little contaminant mass remains in fractures, and that groundwater contamination at the Site is present in a sandstone matrix. These factors together suggest that ISTR may be applicable.

- The detailed understanding of the groundwater flow regime in and immediately surrounding the target treatment zone. This includes the ability to predict and control the hydraulic gradient under conditions of ISTR operation. Although the site conceptual model (Cherry, 2009) indicates that the groundwater flow as well as the fate and transport of TCE is well understood at this site, there will likely be treatment-area specific details that need to be understood before applying ISTR technology. Once target treatment zones for ISTR are defined, it will be critical to develop a detailed understanding of groundwater hydraulics to ensure proper heating will occur in the treatment zone is essential to effective ISTR treatment. This likely will entail inclusion of some type of hydraulic control to limit groundwater flow into the treatment zone.

Because of the depths of the potential ISTR applications at the Site, careful consideration would need to be given to the liquid and vapor extraction systems, as well as the above ground treatment equipment. Also, drilling and system installation costs will be very expensive. Overall,

the available literature on ISTR applications suggests that ISTR is technically feasible for the Site and should be further evaluated as a potential remedial alternative in the future CMS analyses conducted by each of the parties.

In conclusion, the papers reviewed during the development of this paper have identified applications of thermal that have successfully removed significant mass of VOCs from fractured bedrock resulting in appreciable reduction of VOC concentrations in groundwater. These successes also greatly reduced the time frame for contaminant extraction using SVE alone.

Candidate locations at SSFL where thermal may be considered are locations with a bedrock fracture network that would facilitate transport, via SVE, of contaminants to the surface for treatment. Also, locations where the contaminant mass is harbored in the upper bedrock matrix, particularly at the weathered bedrock/competent bedrock interface. Thermal could also be considered for locations where the upper portion of groundwater is impacted by VOCs greater than 1,000 µg/L.

Although none of the case studies attempted thermal treatment greater than 110 feet bgs, there is no technical reason why thermal would not be effective deeper. This conclusion recognizes, however, that there would be additional logistical and practical issues that would need to be addressed. These include knowledge of the extent of contaminant mass at depth, maintaining required temperature controls in the zone of contamination, and the presence of interconnected fractures needed for contaminant transport (heating of the bedrock would be of no use if the VOCs cannot be transported to the surface). However, in essence, any location that could be a candidate for SVE contaminant removal, could also be a candidate for thermal enhance extraction.

Section 8
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Appendix A
Literature Database

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Appendix A. Thermal Treatment Literature Database

Title	Author	Year of Publication	Type of Publication	Source of Publication	Type of Study	Study objective	Thermal Technology	Contaminants of Concern	Lithology	Max Treatment Depth	Energy Sources	Target/achievable temperature	Site	Contamination Removal	Additional Removal Activities	Total project cost	Treatment unit cost ($/cy)	Brief Summary/Noteworthy findings
Enhanced Removal of Residual DNAPL with Hot Water Injection	Bjorn, A.	2000	Thesis	University of Toronto	Bench-scale	Feasibility	Hot water injection	DNAPL	NA	NA	NA	Variable	Laboratory	NA	NA	NA	NA	A bench-scale treatability was conducted to study the impacts of hot water recirculation on DNAPL extraction. Simulations were run to evaluate preferential flows and effects of temperature on DNAPL dissolution. Results showed that preferential flows were not significant over long periods of time. Variable temperatures tend to result improved DNAPL recovery.
Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment	ESTCP	2009	State-of-the-Practice Overview	ESTCP	Literature review	State of the practice	Various	Various	Various	N/A	NA	NA	NA	NA	NA	NA	NA	State of the practice overview
Unified Facilities Criteria Design: In Situ Thermal Remediation	Department of Defense	2006	State-of-the-Practice Overview	Department of Defense	Design	Design & optimization	Various	Various	Various	N/A	NA	NA	NA	NA	NA	NA	NA	State of the practice overview
Groveland Wells Numbers 1 and 2 Superfund Site — Operable Unit 2: Final Remedial Action Report U.S. EPA Region 1	USEPA	2011	Report	Clu-in	Field	Implementation	ET-DSP	TCE	NA	Up to 45 feet	NA	90°C	Groveland Wells Numbers 1 and 2 Superfund Site — Operable Unit 2, Groveland, Massachusetts	99% and 75% removal of TCE and cis-DCE in GW, respectively		$6,264,000	$359	
Steam Enhanced Extraction and Electro-Thermal Dynamic Stripping Process (ET-DSP) at the Young-Rainy Star Center (formerly Pinellas) Northeast Area A, Largo, Florida	US DOE	2003	Report	NA	Field	Implementation	Steam enhanced extraction & ET-DSP	NAPL	Fine-grained sand underlain by clay	35 feet	NA	> 84°C	Young-Rainy Star Center (formerly Pinellas) Northeast Area A, Largo, Florida	99.93% treatment efficiency for all VOCs. Near attainment of MCLs achieved		$3,800,000	NA	
A practical approach to steam-enhanced dual-phase extraction: A case study.	Bouchard, D. P., T. M. Musterait and J. A. Sobieraj	2003	Peer-reviewed journal	Remediation Journal	Pilot	Feasibility	Steam enhanced extraction	SVOCs	Urban fill	Up to 10 feet	Fuel oil	> 100°C	Former industrial site in NY	Orders of magnitude decreases in total VOCs; 65% reduction in phenol		$2,600,000	$67	- Pilot study to evaluate the feasibility and effectiveness of steam-enhanced DPE for treatment of VOCs and SVOCs at a former industrial site in NY
Americium/curium vitrification process development. Part II	Fellinger, A. P., M. A. Baich, J. W. Duvall, et al.	2000	Peer-reviewed journal	Materials Research Society	Basis of design	Implementation	Vitrification	Americium & curium	NA	NA	NA	1450°C	Savannah River Site in Aiken, South Carolina.	NA	NA	NA	NA	- Development report on pilot-scale vitrification for stabilization and storage of americium and curium at the Savannah River Site
An analysis of a mixed convection associated with thermal heating in contaminated porous media	Krol, M. M., R. L. Johnson and B. E. Sleep	2014	Peer-reviewed journal	Science of the Total Environment	Modeling	Optimization	Electrical resistance heating	VOCs	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Electro-thermal model was used to evaluate the effects of heating on 16 subsurface scenarios of varying groundwater fluxes and soil permeabilities. Buoyant flow occurring under clay layers can lead to mass accumulation and
Application of nonisothermal multiphase modeling to in situ soil remediation in soderkulla	Kling, T., J. Korkealaakso and J. Saarenpaa	2004	Peer-reviewed journal	Vadose Zone Journal	Modeling	Design & optimization	Steam enhanced extraction	TCE										
Assessment of Groundwater Quality Improvements and Mass Discharge Reductions at Five In Situ Electrical Resistance Heating Remediation Sites	Triplett Kingston, J. L., P. R. Dahlen and P. C. Johnson	2012	Peer-reviewed journal	Ground Water Monitoring and Remediation	Literature review	Performance evaluation	Electrical resistance heating	Chlorinated solvents, BTEX	Permeable sediments and impermeable sediments	37 feet	NA	89°C to 100°C	Various	Less than 10x and up to 100x mass discharge reductions	NA	NA	NA	- Remediation to groundwater standards is possible with thermal for some sites - Spatial extent of source zone needs to be fully defined and encompassed in thermal implementation to achieve desirable results
Co-injection of air and steam for the prevention of the downward migration of DNAPLs during steam enhanced extraction: An experimental evaluation of optimum injection ratio predictions	Kaslusky, S. F. and K. S. Udell	2005	Peer-reviewed journal	Journal of Contaminant Hydrology	Research	Optimization	Steam enhanced extraction	DNAPL	Sand	NA	NA	~ 100°C	Laboratory	NA	NA	NA	NA	- Laboratory experiments performed to validate the predicted optimal injection ratios to eliminate accumulation of DNAPL and minimize downward contaminant migration. - Co-injection of steam and air was shown to result in much higher recovery rates than air injection alone
Combining Different Frequencies for Electrical Heating of Saturated and Unsaturated Soil Zones	Roland, U., F. Holzer and F. D. Kopinke	2011	Peer-reviewed journal	Chemical Engineering and Technology	Bench-scale	Feasibility	Electrical resistance heating	BTEX	sand, clay, larger stones, and soil with higher carbon content	3.5 m	Electricity from grid	100°C	Former storage facility for organic solvents in Leipzig, Germany.	NA	On-site treatment with Activated Carbon	NA	NA	- A combination of low-frequency and radio frequency energy for resistive heating was used to overcome the steep temperature gradients that are often observed when using each heating mode individually.
Combining steam injection with hydraulic fracturing for the in situ remediation of the unsaturated zone of a fractured soil polluted by jet fuel.	Nilsson, B., D. Tzovolou, M. Jeczalik, et al.	2011	Peer-reviewed journal	Journal of Environmental Management	Pilot	Implementation	Steam enhanced extraction	Jet fuel	Clay, silt, and till with interbedded sand stringer and fractures	5 m	NA	~ 100°C	Abandoned military airport, North Western Poland	~ 43% - 72% reduction in total hydrocarbons		NA	NA	- Pilot-scale study with steam injection on the unsaturated zone of a strongly heterogeneous fractured soil contaminated with jet fuel - 3 sand-fill hydraulic fractures initiated prior to steam injection - Up to 72% reduction in total hydrocarbons
Construction use of vitrified chromium-contaminated soils.	Meegoda, J. N., W. Kamolpornwijit and G.	2000	Peer-reviewed journal	Practice Periodical of	Field	Reuse	Vitrification	Chromium	NA	NA	NA	NA	Laboratory	NA	NA	NA	NA	- Bench- and pilot-scale feasibility study to evaluate the potential use of vitrified Cr-contaminated soil as construction materials
Demonstration of In Situ Radio-Frequency Heating at a Former Industrial Site.	Holzer, F., D. Buchenhorst, R. Köhler, et al.	2013	Peer-reviewed journal	Chemical Engineering & Technology	Field	Implementation	Radio frequency heating	Hydrocarbons	NA	Up to 5.3 m	NA	54°C	A former hydrotreatment plant in Zeitz near Leipzig	1.4 ton of organic pollutants removed	NA	NA	NA	- Demonstration of in situ radio-frequency heating at a Former Industrial Site contaminated with hydrocarbons - Marked increases in extraction rates of the organic pollutants following heating
Dissolved gas exsolution to enhance gas production and transport during bench-scale electrical resistance heating	Hegele, P. R. and K. G. Mumford	2015	Peer-reviewed journal	Advances in Water Resources	Bench-scale	Optimization	Electrical resistance heating	VOCs	NA	NA	NA	~25°C	Laboratory	NA	NA	NA	NA	- Condensation of VOCs in colder zones of a treatment area can adversely affect the performance of ISTR - Bench-scale ERH experiments were performed with dissolved CO2 and NaCl solution to evaluate exsolved gas saturations and transport regimes at elevated but sub-boiling temperatures - Results show that ERH-activated CO2 exsolution can increase gas production at sub-boiling temperatures
Dynamic immobilization of simulated radionuclide 133Cs in soil by thermal treatment/vitrification with nanometallic Ca/CaO composites.	Mallampati, S. R., Y. Mitoma, T. Okuda, et al.	2015	Peer-reviewed journal	Journal of Environmental Radioactivity	Bench-scale	Feasibility	Vitrification	Radionuclide	NA	NA	NA	1200°C	Laboratory with soil from Okayama prefecture, Japan	Up to 99% immobilization	NA	NA	NA	- Vitrification with Ca/CaO amendment for immobilization of 133Cs - Addition of nano-metallic Ca/CaO and fly ash may be potentially applicable for treatment of Cs-contaminated soil at zero evaporation and at relatively low temp.
Effect of temperature on cosolvent flooding for the enhanced solubilization and mobilization of NAPLs in porous media	Aydin, G. A., B. Agaoglu, G. Kocasoy, et al	2011	Peer-reviewed journal	Journal of Hazardous Materials	Bench-scale	Feasibility	Combined technique: hot water & co-solvent flushing	Toluene NAPL	NA	30 cm column	NA	20°C to 40°C	Laboratory	Up to 94% recovery	NA	NA	NA	- Batch experiments were conducted to study the effects of temperature on fluid properties and ethanol-water-toluene system where ethanol ranged from 20-100% by mass - The impacts of hot water on NAPL recovery were most pronounced at 40-60% ethanol by mass - Coupling hot water with insitu cosolvent washing may be a potentially effective remedial alternative
Electrode Design for Soil Decontamination with Radio-Frequency Heating.	Roland, U., F. Holzer, M. Kraus, et al.	2011	Peer-reviewed journal	Chemical Engineering & Technology	Research	Design & optimization	Radio frequency heating	NA	NA	NA	NA	NA	Laboratory	NA	NA	NA	NA	- Design considerations for different type of radio-frequency heating electrodes in soil remediation
Electro-Thermal Dynamic Stripping Process for in situ remediation under an occupied apartment building	Bruce, C. W. M.	2003	Peer-reviewed journal	Remediation Journal	Field	Implementation	ET-DSP	BTEX		5.5 m	NA	~ 80°C	Residential apartment building	- Pre-treatment > 7.5 ppm benzene - Post-treatment < 0.02 ppm benzene		NA	$80	- ET-DSP with high-vacuum dual phase extraction were successfully used to remediate benzene-contaminated soil underneath an occupied apartment complex - The implemented technology was not limited by depth
Engineering aspects of radio-wave heating for soil remediation and compatibility with biodegradation	Roland, U., D. Buchenhorst, F. Holzer, et al.	2008	Peer-reviewed journal	Environmental Science and Technology	Literature review	Optimization	Radio frequency heating	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Combination of low- and high-frequency electrical energy for heating the capillary fringe - Radio-frequency heating can be used to aid bioremediation
Full-Scale Removal of DNAPL Constituents Using Steam-Enhanced Extraction and Electrical Resistance Heating	Heron, G., S. Carroll and S. G. Nielsen	2005	Peer-reviewed journal	Ground Water Monitoring & Remediation	Field	Implementation	Combined technique: ERH & SEE	TCE, cis-1,2 DCE, methylene chloride, toluene, and petroleum hydrocarbons	Sand and clay	35 feet	NA	100°C	Area A of the Northeast Site at the Young-Rainey STAR Center, Largo, Florida	Remedial efficiencies of between 99.85% and 99.99% for the four chemicals of concern		NA	NA	- Removal of all contaminants of concern to below or close to groundwater MCLs within 4.5 months of thermal operation - Post-thermal polishing was not needed

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Title	Author	Year of Publication	Type of Publication	Source of Publication	Type of Study	Study objective	Thermal Technology	Contaminants of Concern	Lithology	Max Treatment Depth	Energy Sources	Target/achievable temperature	Site	Contamination Removal	Additional Removal Activities	Total project cost	Treatment unit cost ($/cy)	Brief Summary/Noteworthy findings
Gas production and transport during bench-scale electrical resistance heating of water and trichloroethene	Hegele, P. R. and K. G. Mumford	2014	Peer-reviewed journal	Journal of Contaminant Hydrology	Bench-scale	Optimization	Electrical resistance heating	TCE	Unconsolidated silica sand	NA	Electric current	100°C	NA	NA	NA	NA	NA	- Laboratory studies suggested that the subsurface should be heated to water boiling temperatures to facilitate gas transport from DNAPL hot spots to extraction points and reduce the potential for DNAPL redistribution
Hot water flushing for immiscible displacement of a viscous NAPL	O'Carroll, D. M. and B. E. Sleep	2007	Peer-reviewed journal	Journal of Contaminant Hydrology	Bench-scale	Feasibility	Hot water injection	NAPL	Sand	NA	NA	50°C	Laboratory	75% NAPL mass recovery	NA	NA	NA	- Bench-scale, sandbox experiments conducted to investigate if hot water flooding techniques would improve NAPL mass removal compared to ambient temperature water flushing - Hot water flooding was shown to reduce the size of the high NAPL saturation zone and yield greater mass recovery - Hot water flooding *did not* result in lower residual NAPL saturations
Hydraulic characterization for steam enhanced remediation conducted in fractured rock	Stephenson, K. M., K. Novakowski, E. Davis, et al.	2006	Peer-reviewed journal	Journal of Contaminant Hydrology	Field	Implementation	Steam enhanced extraction	VOCs (PCE mainly)	Fractured limestone	30-95 feet	Diesel-fired steam generator	100°C	Loring Air Force Base in northern Maine	More than 7.4 kg of contaminants were recovered, of which 5.0 kg were chlorinated VOCs, 0.55 kg were gasoline range organics (GRO), and 1.77 kg were diesel range organics (DRO).	Air stripping, Soil vapor extraction (SVE), Off-gas treatment	NA	NA	- Hydraulic characterization tools including the pulse interference tests were used in assisting with the design of the injection/extraction well geometry and in predicting the migration pathways of the hot water associated with the steam injection
In situ plasma remediation of metals and radionuclides in soil	Abbott, E. H., J. T. Bell, R. A. Fjeld, et al. (2002)	2002	Peer-reviewed journal	Center for Research and Technology Development	Literature review	Feasibility	Vitrification	Heavy metals & radionuclides										
In Situ Radio-Frequency Heating for Soil Remediation at a Former Service Station: Case Study and General Aspects.	Huon, G., T. Simpson, F. Holzer, et al. (2012)	2012	Peer-reviewed journal	Chemical Engineering & Technology	Field	Implementation	Radio frequency heating	Hydrocarbons				50°C	A former petrol station					
In situ thermal remediation of DNAPL and LNAPL using electrical resistance heating	Beyke, G. and D. Fleming	2005	Peer-reviewed journal	Remediation Journal	Pilot	Implementation	Electrical resistance heating	TCE	Alluvium	100 feet	NA	~ 90°C	U.S. DOE Paducah Gaseous Diffusion Plant in Kentucky	Concentrations of TCE were reduced by an average of 98% in soil and 99% in groundwater.	On-site treatment with Activated Carbon	NA	$40-$70	
In situ thermal remediation of DNAPL and LNAPL using electrical resistance heating	Beyke, G. and D. Fleming	2005	Peer-reviewed journal	Remediation Journal	Field	Implementation	Combined technique: ERH & Multiphase extraction	Chlorinated solvents, TCE, petroleum products, oil and lubricants	Sandy with clay/silt	2-38 feet	NA	90°C in vadose zone to 100°C in saturated zone	East Gate Disposal Yard, Fort Lewis, Washington.	87% reduction in TCE concentrations in groundwater	Vapors are being treated using a 1,000 cfm thermal oxidizer equipped with an acid gas scrubber.	NA	$40-$70	
In-field remediation of tons of heavy metal-rich waste by Joule heating vitrification	Dellisanti, F., P. L. Rossi and G. Valdre	2009	Peer-reviewed journal	International Journal of Mineral Processing	Field	Implementation	Vitrification	Heavy metals										
Influence of in Situ Steam Formation by Radio Frequency Heating on Thermodesorption of Hydrocarbons from Contaminated Soil	Roland, U., S. Bergmann, F. Holzer, et al.	2010	Peer-reviewed journal	Environmental Science & Technology	Bench- and pilot-scale	Feasibility	Radio frequency heating	Hydrocarbons	Sand	NA	NA	100°C	Artificially contaminated sand & contaminated soil from an industrial site			NA	NA	- Bench-scale study of radio-frequency heating for thermal desorption of contaminants from soil - Pilot study at an industrial site; up to 90% reduction in contaminant concentrations
Life-cycle assessment of in situ thermal remediation	Fisher, A.	2012	Peer-reviewed journal	Remediation Journal	Life cycle analysis	Life cycle cost analysis	ISTR	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Life cycle assessment of ISTR
Material Flow Analysis: An Effectiveness Assessment Tool for In Situ Thermal Remediation	Laumann, S., V. Micic, J. Fellner, et al.	2013	Peer-reviewed journal	Vadose Zone Journal	Material flow analysis	Optimization	In situ thermal desorption	Chlorinated solvents, PCE	Rock-fill, gravel, silt, sand	7 m	NA	NA	Former dry cleaning facility, Lower Austria	The total chlorinated solvent mass extracted from the test site by ISTD and P&T was ~360 ± 10 kg.	Soil vapor extraction (SVE), Pump and treat (P&T), On-site treatment with Activated Carbon	NA	NA	- 1st time use of material flow analysis to evaluate the effectiveness of ISTR - High effectiveness in contaminant removal and time efficiency were reported
Microbial activity in soils following steam treatment	Richardson, R. E., C. A. James, V. K. Bhupathiraju, et al.	2002	Peer-reviewed journal	Biodegradation	Bench-scale	Research	Steam enhanced extraction	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Laboratory and field studies of microbial activities in soil following steam treatment - Results showed that organisms capable of biodegradation can survive steam treatment
Microcosm evaluation of bioaugmentation after field-scale thermal treatment of a TCE-contaminated aquifer	Friis, A. K., J. L. L. Kofoed, G. Heron, et al.	2007	Peer-reviewed journal	Biodegradation	Bench-scale	Optimization	Electrical resistance heating	TCE	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Bench-scale microcosm studies using post-thermal treatment aquifer materials - Reductive dechlorination is possible in field-scale thermal treatment - Optimal bioaugmentation temperature is approximately 30°C
Microwave heating applications in environmental engineering—a review	Jones, D. A., T. P. Lelyveld, S. D. Mavrofidis, et al.	2002	Peer-reviewed journal	Resources, Conservation & Recycling	Literature review	State of the practice	Microwave heating	VOCs	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Review of microwave heating applications in environmental engineering
Numerical analysis of contaminant removal from fractured rock during boiling	Chen, F., R. W. Falta and L. C. Murdoch	2012	Peer-reviewed journal	Journal of Contaminant Hydrology	Modeling	Optimization	Electrical resistance heating	1,2-DCA	Sandstone	NA	Electric current	100 °C	Laboratory experiment based numerical model	> 99%	NA	NA	NA	- Multiphase heat transfer numerical model was used to simulate ISTR in fractured rock - Modeling results showed that boiling out 1/2 pore volume of water results in near 100% removal efficiency - Field scale simulation showed that 28% extraction of pore volume results in more than 99% removal of contaminant mass
Numerical Simulation of a Steam-Injection Pilot Study for a PCP-Contaminated Aquifer	Tse, K. K. C., L. Tai-Sheng and L. Shang-Lien	2006	Peer-reviewed journal	Environmental Science & Technology	Modeling	Optimization	Steam enhanced extraction	PCP	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Numerical simulation for insights on heat transfer and contaminant transport during steam injection at a PCP-contaminated aquifer - PCP transport was determined to be more sensitive to the vertical permeability than partitioning coefficient - Steam injection rate is a very important design and operating parameter
Optimizing the environmental performance of in situ thermal remediation technologies using life cycle assessment	Lemming, G., S. G. Nielsen, K. Weber, et al	2013	Peer-reviewed journal	Groundwater Monitoring and Remediation	Life cycle analysis	Optimization	Various	Chlorinated solvents	Low to high permeability source zone	7-9 m	Natural gas, electricity	100°C	Two contaminated sites—a smaller (180 m^2) and a larger site (1300 m^2) representing two typical Danish sites where remediation using ISTD has been conducted.	NA	NA	NA	NA	- A detailed investigation of the four ISTR techniques was performed to compare the life cycle environmental impacts and resource consumption as well as to identify options to reduce these adverse effects - Some options for environmental optimization include increasing off-peak electricity use, reducing the amount of concrete in the vapor cap, using SS for heater wells, etc...
Pilot Study of In-Situ Thermal Treatment for the Remediation of Pentachlorophenol-Contaminated Aquifers	Tse, K. K. C., S.-L. Lo and J. W. H. Wang	2001	Peer-reviewed journal	Environmental Science & Technology	Pilot	Implementation	Hot air injection	PCP	Silty sand	10 m	NA	118°C	Former PCP-manufacturing plant	~ 70% PCP removal in soil	-	$140,000	$25	- 3-month pilot study of hot steam injection at a PCP-contaminated aquifer - Steam injection can be used to aid thermal desorption of PCP from soil - Dramatic PCP reduction in the deep aquifer while increases were seen in the shallow soil

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Title	Author	Year of Publication	Type of Publication	Source of Publication	Type of Study	Study objective	Thermal Technology	Contaminants of Concern	Lithology	Max Treatment Depth	Energy Sources	Target/achievable temperature	Site	Contamination Removal	Additional Removal Activities	Total project cost	Treatment unit cost ($/cy)	Brief Summary/Noteworthy findings
Radio Frequency Heating for Soil Remediation.	Price, S. L., R. S. Kasevich, M. A. Johnson, et al.	1999	Peer-reviewed journal	Journal of the Air & Waste Management Association (Air & Waste Management Association)	Literature review	State of the practice	Radio frequency heating	GRO	NA	~ 10 feet	NA	100°C	Laboratory bench study then pilot at a former gas station near St. Paul, MN	50% reduction in overall GRO	NA	NA	NA	- Bench- and field-scale application of radio frequency heating for treatment of GRO-contaminated soil
Remediation of asbestos containing materials by Joule heating vitrification performed in a pre-pilot apparatus	Dellisanti, F., P. L. Rossi and G. Valdre	2009	Peer-reviewed journal	International Journal of Mineral Processing	Pilot	Feasibility	Vitrification	Asbestos	NA	NA	NA	1600°C	NA	Complete melting of fibrous materials	NA	NA	NA	- Pre-pilot scale demonstration of vitrification by Joule heating for remediation of asbestos-containing materials
Remediation of elemental mercury using in situ thermal desorption (ISTD)	Kunkel, A. M., J. J. Seibert, L. J. Elliott, et al.	2006	Peer-reviewed journal	Environmental Science and Technology	Bench-scale	Feasibility	In situ thermal desorption	Mercury	Sand	NA	NA	600°C	Laboratory	99.8% removal of mercury	NA	NA	NA	- Bench-scale demonstration of ISTD for treatment of mercury in Ottawa sand - 99.8% removal was achieved
Removal of NAPLs from the unsaturated zone using steam: prevention of downward migration by injecting mixtures of steam and air	Schmidt, R., J. Gudbjerg, T. O. Sonnenborg, et al.	2002	Peer-reviewed journal	Journal of Contaminant Hydrology	Bench-scale	Feasibility	Steam/air injection	NAPL	NA	NA	NA	NA	Laboratory	NA	NA	NA	NA	- Modification of steam injection technology that incorporates both steam and air to minimize downward contaminant migration - Three mechanisms for contaminant removal were identified - It was shown that the effectiveness of these mechanisms depends on the air-to-steam mixing ratio
Removal of NAPLs from the unsaturated zone using steam: prevention of downward migration by injecting mixtures of steam and air	Schmidt, R., J. Gudbjerg, T. O. Sonnenborg, et al.	2002	Peer-reviewed journal	Journal of Contaminant Hydrology	Bench-scale	Feasibility	Hot air injection											
Removal of PCE DNAPL from Tight Clays Using In Situ Thermal Desorption	Heron, G., J. Lachance and R. Baker	2013	Peer-reviewed journal	Ground Water Monitoring & Remediation	Field	Implementation	In situ thermal desorption	PCE, TCE, cis-1,2-DCE, and vinyl chloride	Clay	6.2 m	Electricity from grid	100°C to 400°C	Terminal One site, located at Point Richmond in San Francisco Bay, California.	Approximately 2540 kg of contaminants were recovered in the extracted vapors by the end of treatment. Maximum % Reduction: PCE = 99.99% TCE = 99.70% cis-1,2-DCE = 98.28% VC = 99.27%	Soil vapor extraction (SVE), Off-gas treatment	NA	NA	- PCE in clay was reduced from as high as 2,700 mg/kg to 0.012 mg/kg within 110 days of heating - ~ 45% of the electricity was used for heating the subsurface to target temp - ~ 53% of the electricity was used for boiling GW - Robust design includes heaters extending 1.2 m beyond the treatment depth & installation of shallow horizontal vapor recovery wells
Results of Field Tests on Radio-Wave Heating for Soil Remediation	Roland, U., F. Holzer, D. Buchenhorst, et al.	2007	Peer-reviewed journal	Environmental Science & Technology	Field	Implementation	Radio frequency heating	Hydrocarbons	Gravelly, sandy soil	NA	NA	35°C to 100°C	Hirschfeld, Saxony, Germany	Some decreases in hydrocarbon concentrations	NA	NA	NA	- Bioremediation and radio-frequency heating application for ex situ cleaning of soil
Results of Field Tests on Radio-Wave Heating for Soil Remediation	Roland, U., F. Holzer, D. Buchenhorst, et al.	2007	Peer-reviewed journal	Environmental Science & Technology	Field	Implementation	Radio frequency heating	Hydrocarbons	NA	NA	NA	100°C	Former storage facility for organic solvents in Leipzig, Germany.	2-3 fold increase in extraction rate	NA	NA	NA	- Bioremediation and radio-frequency heating application to aid in situ remediation at a former storage facility for organic solvents
Results of Field Tests on Radio-Wave Heating for Soil Remediation	Roland, U., F. Holzer, D. Buchenhorst, et al.	2007	Peer-reviewed journal	Environmental Science & Technology	Field	Implementation	Radio frequency heating	Hydrocarbons	NA	NA	NA	NA	Former petrol station, Hoyerswerda in Saxony, Germany	Up to 8 fold increase in extraction rate	NA	NA	NA	- Bioremediation and radio-frequency heating application for treatment of polluted soil under a gas station
Review of in situ remediation technologies for lead, zinc, and cadmium in soil	Martin, T. A. and M. V. Ruby	2004	Peer-reviewed journal	Remediation Journal	Literature review	State of the practice	Various	Heavy metals	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Review of in situ treatment technologies for lead, zinc, and cadmium in soil
Role of NAPL thermal properties in the effectiveness of hot water flooding	O'Carroll, D. M. and B. E. Sleep	2009	Peer-reviewed journal	Transport in Porous Media	Modeling	Optimization	Hot water injection	LNAPL, coal tar	NA	NA	NA	10°C to 90°C	Undisclosed site	NA	NA	NA	NA	- Simulations were run using 16 different geostatistical representations and 2 types of NAPLs to evaluate the effectiveness of hot water flushing - Results showed that flooding with water of elevated temperatures resulted in enhanced recovery of both NAPLs
Soil heating for enhanced remediation of chlorinated solvents: A laboratory study on resistive heating and vapor extraction in a silty, low- permeable soil contaminated with trichloroethylene	Heron, G., M. Van Zutphen, T. H. Christensen, et al.	1998	Peer-reviewed journal	Environmental Science and Technology	Bench-scale	Feasibility	Thermal conductive heating	TCE	Silty soil	50 cm laboratory tank	Electric current	85°C to 100°C	Laboratory experiment	99.8% mass removal	Soil vapor extraction (SVE)	NA	NA	- 99.8% TCE mass removal after 37 days of heating in laboratory study
State-of-the-practice review of in situ thermal technologies	Triplett Kingston, J. L., P. R. Dahlen and P. C. Johnson	2010	Peer-reviewed journal	Ground Water Monitoring and Remediation	Literature review	State of the practice	Various	Chlorinated solvents, petroleum hydrocarbons, wood treating, various	Permeable sediments and impermeable sediments, fractured bedrock, weathered bedrock, limestone and sandstone	NA	NA	< 80°C to >110°C	182 applications were reviewed, which included 87 ERH, 46 steam-based heating, 26 conductive heating, and 23 other heating technology applications conducted between 1988 and 2007.	Less than 10x and up to 100x mass discharge reductions	NA	NA	NA	
The mechanisms of electrical heating for the recovery of bitumen from oil sands	McGee, B. C. W. and F. E. Vermeulen	2007	Peer-reviewed journal	Journal of Canadian Petroleum Technology	Literature review	Optimization	ET-DSP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	- A finite element electromagnetic model was used to describe the dominant mechanisms of the electrical heating recovery process of bitumen from oil sands
Thermal treatment of eight CVOC source zones to near nondetect concentrations	Heron, G., K. Parker, J. Galligan, et al.	2009	Peer-reviewed journal	Ground Water Monitoring and Remediation	Field	Implementation	In situ thermal desorption	CVOCs: PCA, DC, 1,2-DCE, carbon tetrachloride, chloroform, methylene chloride, PCE, TCE & vinyl chloride	Low permeability loess over high permeability alluvium	30 feet	Electricity from grid	90°C to 100°C	Memphis Depot in southeastern Memphis, Tennessee.	Estimated total of 5675 kg of VOCs removed in vapor phase. Generally, the reduction in concentration was on the order of 99.99% for CVOCs that were present in high concentrations before the thermal treatment.	A central treatment system, based on condensation and granular activated carbon filtration, was used to treat the vapors.	$3,900,000	$79	- Target treatment goals were achieved in all high concentration areas after 177 days
World's Largest In Situ Thermal Desorption Project: Challenges and Solutions.	Heron, G., K. Parker, S. Fournier, et al.	2015	Peer-reviewed journal	Groundwater Monitoring and Remediation	Field	Implementation	In situ thermal desorption	Chlorinated solvents	Fill, sand, silt, and clay	19 to 40 feet	NA	100°C	A former aerospace manufacturing facility adjacent to a commercial airport	An estimated 13,400 kg (29,800 lbs) of CVOC mass was removed, and all soil goals were met.		NA	NA	- Largest ISTD project in the world

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Ground Water Issue - Steam Injection for Soil and Aquifer Remediation.	Davis, E.	1998	EPA	EPA groundwater issue	Literature review	State of the practice	Hot air injection				NA							
Advanced characterization and treatability tests lead to decision on combined thermal and biological remediation at a PCE/TCE/TCA site	Tuxen, N., K. L. Andersen, H. Kerrn-Jespersen, et al	2009	Conference proceeding	Battelle	Bench- & field-scale	Implementation	Combined technique: ISTD & bio	PCE, TCE, 1,1,1-TCA & hydrocarbons	Clayey till	NA	NA	NA	Former solvent storage and distribution facility in the Capital Region of Copenhagen, Denmark	NA	Stimulated Reductive Dechlorination (SRD)	NA	NA	- Use of advanced characterization tools and treatability testing leads to the decision on combined technique for full-scale remedy at a chlorinated solvent site
Advances in the application of in situ electrical resistance heating	Smith, G. J. and G. Beyke	2009	Conference proceeding	ICEM	Literature review	State of the practice	Electrical resistance heating	Various	Various	NA	NA	NA	Overview of 75 different applications	NA	NA	NA	NA	- Overview of technological advances in ISTR applications
Analysis of optical emission spectroscopy from arcs for plasma vitrification of hazardous wastes	Rodriguez-Yunta, A., C. Pardo and M. A. G. Calderon	2004	Conference proceeding	31st IEEE International Conference on Plasma Science	Laboratory	Research	Vitrification											
Characterization of glass from a vitrification demonstration at Los Alamos National Laboratory	Coel-Roback, B. J. and D. M. Timmons (2005)	2005	Conference proceeding	10th International Conference on Environmental Remediation and Radioactive Waste Management	Laboratory	Research	Vitrification											
Combining In Situ Thermal Treatment and Bioremediation to Remediate a Large Chlorinated Solvent Site	Perlmutter, M.	2013	Conference proceeding	Battelle	Field	Implementation	Combined technique: thermal & bio	CVOCs	Sand and silt	100 feet	NA	93°C	Grants Chlorinated Solvents Plume Superfund Site in Grants, New Mexico	99% reduction in soil	Bioremediation in downgradient plume	NA	NA	- Combining ISTR & bio for treatment of a large PCE site
Combining Low-Energy Heating with Biotic and Abiotic Treatment for DNAPL Sources	Macbeth, T.	2010	Conference proceeding	Battelle	Field	Demonstration	Combined technique: thermal & ISCR & bio	TCE	NA	NA	NA	up to 55°C	NA	NA	ZVI	NA	NA	- Thermally enhanced biotic and abiotic destruction of DNAPL sources
Complete In Situ Reduction of DNAPL Source Zones Using Combined Thermal and ZVI Soil Mixing	Faircloth, h.	2010	Conference proceeding	Battelle	Field	Implementation	Combined technique: steam & ISCR	TCE	NA	55 feet	NA	NA	Cape Canaveral Air Force Station	99.8% removal of contaminants of concern	ZVI via LDA	$19,598,000	$190	- Thermal and ZVI soil mixing for complete reduction of DNAPL source zones
Completion of in-situ thermal remediation of PAHs, PCP and dioxins at a former wood treatment facility	Baker, R. S., D. Tarmasiewicz, J. M. Bierschenk, et al.	2007	Conference proceeding	International Conference on Incineration and Thermal Treatment Technologies	Field	Implementation	ISTD/Thermal conductive heating	PAHs, PCP & dioxins	Fine, silty sand	105 feet	NA	335°C	Former wood treatment facility in Alhambra, California	Clean up levels achieved for all contaminants of concerns	Oxidizer	$6,330,000	$650	- ISTD application for treatment of PAHs, PCP, and dioxins at a former wood treatment facility in CA
Effect of Thermal Treatment on a Chlorinated Solvent-Degrading Microbial Community	Blackmore, W.	2007	Conference proceeding	Annual International Conference on Soils Sediments and Water	Bench-scale	Research: microbial	Various	NA	NA	NA	NA	NA	East Gate Disposal Yard, Fort Lewis,Washington.	NA	NA	NA	NA	- Bench-scale study performed to evaluate the post-thermal effects on cVOC-degrading microbes
Effects of Thermally Enhanced Soil Vapour Extraction (TESVE) on Indigenous Microbial Communities and Continued Biological Reduction of Chlorinated Solvents in Chalk in the United Kingdom	Kozlowsak, A. M.	2010	Conference proceeding	Battelle	Field	Research: microbial	In situ thermal desorption	PCE	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Bench-scale study conducted to evaluate the effects of ISTR operations on microbes - Post-thermal conditions promote growth of select bacteria that are desirable for bioremediation - Thermally-enhanced bio can serve as a final polishing step for thermal
Electrical Resistance Heating for DNAPL Source Removal at Alameda Point	Cacciatore, D.	2008	Conference proceeding	Battelle	Field	Implementation	Electrical resistance heating	CVOCs	Bay sediment and artificial till	45 feet	NA	100°C	Alameda Point, Installation Restoration (IR) Sites 4 and 5, Alameda, California	up to 99.6% reduction	NA	NA	NA	- ERH application for DNAPL source removal
Electrical Resistance Heating of a TCE Source Zone beneath an Active Stormwater Detention Basin	Jacob, C.	2008	Conference proceeding	Battelle	Field	Implementation	Electrical resistance heating	TCE	Sand & silty sand	75 feet	NA	NA	The Boeing Company's manufacturing plant in Everett, Washington	Treatment goals of 500 ppb TCE in GW achieved in north 1/2 of treatment area	NA	NA	NA	- ERH application for treatment of TCE source zone
Electrical resistance heating of soils at c-reactor at the savannah river site	Farrar, M. E., M. R. Morgenstern, J. A. Amari, et al	2010	Conference proceeding	Annual International Conference on Soils Sediments and Water	Field	Implementation	Electrical resistance heating	TCE	Clayey sand, sandy clay	62 feet	Electricity from grid	> 200°C	Savannah River Site in Aiken, South Carolina.	A total of 730 lbs of trichloroethylene (TCE) were removed over this period, and subsequent sampling indicated a removal efficiency of 99.4%.	SVE followed by gas treatment. Condensed vapors taken to off-site air stripper before releasing to atmosphere.	NA	NA	- Design, operation, and performance data associated with an ERH application for TCE destruction at the Savannah River Site
Electrical resistance heating under an active industrial plant	Fain, S., C. Holloway, W. Heath, et al.	2002	Conference proceeding	Battelle	Pilot	Implementation	Electrical resistance heating	TCE	Alluvium overlying limestone and/or shale bedrock	35 feet	Electricity from grid	87°C to 100°C	Air Force Plant 4 (AFP4) in Fort Worth, Texas	95% reduction in groundwater concentration Approximately 330 lb of TCE was removed	Soil vapor extraction (SVE), Air stripping, Enhanced biodegradation	NA	$130	-Pilot-scale demonstration of ERH for treatment of TCE DNAPL underneath an active facility
Evaluation of technologies for in situ remediation of 1,1,1-trichloroethane	Cho, H. J., R. J. Fiacco Jr, R. A. Brown, et al.	2002	Conference proceeding	Battelle	Bench-scale	Feasibility	Combined technique: thermal & bio	1,1,1-TCA	Fractured bedrock	NA	NA	NA	Confidential	NA	NA	NA	NA	- Overview of in situ treatment technology for 1,1,1-TCA
Evidence of thermophilic biodegradation for PAHs and diesel in soil	Huesemann, M. H., T. S. Hausmann, T. J. Fortman, et al.	2002	Conference proceeding	Battelle	Bench-scale	Feasibility	Combined technique: thermal & bio	PAHs	NA	NA	NA	25, 50, and 75°C	Laboratory	NA	NA	NA	NA	- Bench scale study to evaluate the potential of thermophilic biodegradation of hydrocarbons in conjunction with ISTR operation
Feasibility Evaluation of Thermal Remediation and Dual-Phase Extraction for Cleanup of a Multicontaminant.	Lo, I.	2010	Conference proceeding	Battelle	Literature review	Feasibility	Combined technique: thermal & DPE	Various	Low permeability, heterogeneous	NA	NA	NA	Former industrial manufacturing and storage site in Oakland, CA	NA	NA	NA	NA	- Bench scale treatability examining ISTR for multiple contaminants included petroleum hydrocarbons, chlorinated solvents, and other VOCs

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Flameless oxidizer treats variable concentration VOCs in thermally enhanced remediation project	Minden, A. C., D. F. Bartz, W. A. Plaehn, et al	2002	Conference proceeding	Battelle	Field	Offgas management	ERH with FTO	VOCs	Landfill	NA	NA	NA	Lowry Landfill Superfund Site (Arapahoe County, Colorado)	99.99% destruction efficiency on all chlorinated and non-chlorinated VOCs	FTO	NA	NA	- Use of ERH and FTO for destruction of chlorinated and non-chlorinated VOCs at the Lowry Landfill Superfund Site in CO
Full-Scale Field Application of S team-Enhanced Dual-Phase Extraction	Musterait, T.	2006	Conference proceeding	Battelle	Field	Implementation	Steam enhanced extraction	SVOCs	Fill	3 m	NA	215F	Former chemical manufacturing facility in Brooklyn, NY	92% reduction in GW SVOC concentrations	DPE	NA	NA	- Steam-enhanced DPE for full-scale treatment of VOCs and SVOCs
Full-Scale In-Situ Soil Mixing Remediation of a Chlorinated DNAPL Source	La Mori, P.	2006	Conference proceeding	Battelle	Field	Implementation	Combined technique: hot air/steam & ISCR	CVOCs	Sandy	55 feet	NA	75°C	Former Space Launch Complex 15 (SLC-15), Cape Canaveral Air Force Station, Florida	99.9% removal for all chlorinated VOCs	ISCR with LDA; FTO	NA	NA	- Full-scale treatment of a DNAPL source using hot air/steam, ZVI via LDA, and FTO
Geomelt vitrification: Status of recent developments and project results	Campbell, B., L. Thompson and K. Finucane	2005	Conference proceeding	10th International Conference on Environmental Remediation and Radioactive Waste Management	Literature review	State of the practice	Vitrification											
Heat-enhanced bioremediation using electrical resistance heating	Beyke, G., T. Powell, M. Truex, et al.	2009	Conference proceeding	Battelle	Literature review	State of the practice	Combined technique: thermal & bio											
Hot air vapor extraction for remediation of petroleum contaminated sites	Fann, S., D. Pal, E. Lory, et al.	1998	Conference proceeding	8th International Offshore and Polar Engineering Conference	Pilot	Feasibility	Hot air injection	TPH					Hydrocarbon National Test Site located at Port Hueneme, California					
Immobilization/vitrification of high concentration lead contaminated soil by applying microwave energy	Tai, H. S., C. G. Jou and H. P. Wang	1997	Conference proceeding	13th International Conference on Solid Waste Technology and Management	Bench-scale	Feasibility	Vitrification	Lead										
In Situ Electro-Thermal Remediation of Chlorinated VOCs: Full-Scale Evaluation	Mejac, M.	2008	Conference proceeding	Battelle	Field	Implementation	Electro-Thermal Dynamic Stripping Process	CVOCs	Silt and clay	24 feet	NA	NA	Industrial site in WI	90-99.8% VOC removal	NA	NA	NA	- Use of ET-DSP for treatment of chlorinated VOCs at an industrial site
In-Situ Thermal Treatment System Performance and Mass Removal Metrics at Fort Lewis. Proceedings	Smith, R.	2006	Conference proceeding	Battelle	Field	Implementation	Electrical resistance heating	TCE	Cobbles, gravel, sand, and silt	55 feet	NA	NA	Fort Lewis East Gate Disposal Yard	97-100% in Area 1 21-92% in Area 2	NA	NA	NA	- Thermal performance evaluation at EDGY
Modelling of steam injection for removal of non-aqueous phase	Cernik, M. and P. Kvapil	2002	Conference proceeding	International Conference on Oil and Hydrocarbon Spills	Modeling	Optimization	Steam enhanced extraction	NAPL										
Modular System Concept For Soil Heating Using Radio-Frequency Energy	Holzer, F., D. Lippik, T. Heimbold, et al.	2010	Conference proceeding	AIP	Research	Conceptual design	Radio frequency heating											
Numerical modelling of steam injection in a vertical sand-filled column.	Emmert, M., R. Helmig and W. Baechle	1997	Conference proceeding	7th Congress of the International Association of Hydraulic Research	Modeling	Optimization	Hot air injection											
Performance of a Large-Scale Combined Bioremediation and In Situ Thermal Treatment Project to Remediate CVOCs and DNAPL	Panciera, M.	2012	Conference proceeding	Battelle	Field	Implementation	Electrical resistance heating	TCE	Till & weathered bedrock	~ 40 feet	NA	95°C	Former manufacturing facility in CT	600 lbs of TCE and ~ 98% of residual mass removed	NA	NA	NA	- Combined techniques including source excavation, ERH, and reductive dechlorination for treatment of TCE at a former manufacturing facility
Radio-frequency (RF) heating applications in environmental technology	Roland, U., M. Kraus, F. Holzer, et al.	2011	Conference proceeding	13th International Conference on Microwave and Radio Frequency Heating	Literature review	State of the practice	Radio frequency heating											
Reactivity and Distribution of Chlorinated Ethenes during Thermal Treatment	Costanza, J.	2012	Conference proceeding	Battelle	Bench-scale	Research: degradation processes	Various											
Remediation and reuse of chromium contaminated soils through cold top ex-situ vitrification	Meegoda, J., B. Librizzi, G. F. McKenna, et al.	1995	Conference proceeding	27th Mid-Atlantic Industrial Waste Conference	Bench-scale	Feasibility	Vitrification	Chromium										
Remediation of a Chlorinated Solvent DNAPL-Impacted Site Using Electrical Resistance Heating	Taddeo, A.	2008	Conference proceeding	Battelle	Field	Implementation	Electrical resistance heating	PCE	Silt and clay	30 feet	Local line	97°C	Former dry cleaning facility	99%	NA	NA	NA	- Use of ERH to treat PCE DNAPL at a former dry cleaning establishment
Remediation of chlorinated VOC by emulsified zero-valent iron (EZVI) emplaced by large diameter auger soil mixing	La Mori, P.	2009	Conference proceeding	Battelle	Field	Implementation	Combined technique: thermal & ISCR	PCE, TCE		20-55 feet								
Results and reaction mechanisms for the treatment of concentrated chlorinated organics using geomelt vitrification	Thompson, L. E.	2002	Conference proceeding	Battelle	Field	Implementation	Vitrification	Chlorinated solvents	NA	NA	NA	Variable	Various	> 99.9999% removal efficiency	NA	NA	NA	- An overview of results and reaction mechanisms for treatment of chlorinated organics using GeoMelt vitrification

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Situ remediation of heavy metal contaminated sites	Hao, Q.	2014	Conference proceeding	International Conference on Vehicle and Mechanical Engineering and Information Technology	Literature review	State of the practice	Various	Heavy metals										
Steam heating increases SVE effectiveness to remove TCE in LNAPL	Larson, L., C. Liles, M. Coons, et al.	2002	Conference proceeding	Battelle	Pilot	Implementation	Steam enhanced extraction	TCE	NA	4-14 feet	NA	100°C	former Chemical Waste Disposal Area at Air Station (NAS) North Island, Coronado, California	Removed over 28,600 pounds of fuel hydrocarbons and VOCs	Soil vapor extraction (SVE)	NA	NA	- Full-scale implementation of steam-enhanced SVE at NI NAS for removal of LNAPL
Sustainability Metrics for Six Selected Commercially Available In Situ and Ex Situ Thermal Remediation Technologies	HUNT, j	2012	Conference proceeding	Battelle	Literature review	Sustainability	Various	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Evaluation of several sustainability metrics for six commercially available in situ and ex situ thermal technologies
Tetrachloroethene source area reduction using electrical resistance heating	Hudson, C., D. Williamson, T. Beisel, et al	2002	Conference proceeding	Battelle	Field	Implementation	Electrical resistance heating	PCE	silt, clay and sand	4-12 feet	Electricity from grid	100°C	Former dry cleaning facility at the Charleston Naval Complex	45.1 % reduction in GW concentration till January 2002, 95% reduction expected by May 2002	SVE and GAC treatment			
Thermal Activation of Contaminant Degradation	Brown, R.	2007	Conference proceeding	Battelle	Literature review	State of the practice	Various											
Thermal Conductive Heating Enhanced DNAPL Source Removal	Fu, A.	2010	Conference proceeding	Battelle	Field	Implementation	Combined technique: thermal & SVE & MPE	CVOCs	NA	16 feet	NA	NA	Former electrical equipment service facility in Jacksonville, FL	NA	NA	NA	NA	-
Thermal Remediation of Deep TCE Contamination at a Site with High Groundwater Flow	Winder, B.	2010	Conference proceeding	Battelle	Field	Implementation	Electro-Thermal Dynamic Stripping Process	TCE	Clay, silt, sand, and gravel overlying bedrock	30 meters	NA	100°C	Operating industrial facility in the central US	NA	NA	NA	NA	- Conceptual design of ISTR for deep TCE contamination
Thermal-enhanced SVE of PCE under a dry cleaning establishment - A case study	Jepsen, J. D., T. Jorgensen, H. Skov, et al.	2002	Conference proceeding	Battelle	Field	Implementation	Steam enhanced extraction	PCE	Sand and silt	~ 4 m	NA	50°c	A dry cleaning establishment has leached from an underground storage tank, Odense, Denmark	285 kg of PCE removed after 1 year of operation	SVE	NA	NA	- Steam injections to enhance SVE at a PCE dry cleaning establishment
Use of Thermal Conduction Heating for the Remediation of DNAPL in Fractured Bedrock	Heron, G.	2008	Conference proceeding	Battelle	Field	Implementation	In situ thermal desorption	TCE	Fractured bedrock	90 feet	Electricity from grid	100°c	Unknown TerraTherm fractured rock site, Southeast US	Total mass of VOCs removed was approximately 12,000 lbs, almost all of which was TCE. 11,590 lbs vapor phase + 92 lbs liquid phase + additional mass lost via hydrolysis and other degradation processes such as direct oxidation or pyrolysis.	Vapor extracted, condensed and sent to groundwater treatment system.	NA	NA	- First full-scale implementation of TCH at a fractured rock site - After ~ 150 days of operations, TCE soil concentrations were reduced to below the remedial goal while groundwater TCE concentrations within the treatment zone were reduced by 75-99.7% - Approximately 12,000 lbs of primarily TCE were removed from the subsurface
Why In Situ Thermal Desorption Can Be the Most Cost-Effective Remediation Method for Many Sites	Baker, R.	2008	Conference proceeding	Battelle	Literature review	Life cycle cost analysis	In situ thermal desorption	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	- Three case studies are present to demonstrate that ISTD is often less expensive than other remedial alternatives
Combing Two Thermal Technologies at the Groveland Wells Superfund Site	TerraTherm	2011	Case Study	TerraTherm	Field	Implementation	Combined technique: ET-DSP & SEE	TCE	Fill, sand, clay, till, bedrock	45 feet	NA	NA	Groveland Wells Superfund Site	95% TCE mass removal	NA	NA	NA	- Combining ET-DSP with shallow steam injections for treatment of TCE
Electro-Thermal Dynamic Stripping Process (ET-DSP): Silresim Chemical Corporation, Lowell, Massachusetts	TerraTherm	2012	Case Study	TerraTherm	Field	Implementation	Electro-Thermal Dynamic Stripping Process	VOCs, BTEX, etc...	Sand, fill, silt, till	90 feet	NA	NA	Silresim Chemical Corporation, Lowell, Massachusetts	39,800 kg of VOCs and 1,580 kg of NAPL	NA	NA	NA	- Application of ET-DSP at a chemical plant for treatment of VOCs and NAPL
Full Scale Implementation of In Situ Thermal Desorption of Tetrachloroethene (PCE) at IBM Owned Site	TerraTherm	2010	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	PCE	Cinder fill, sand, and clay	NA	NA	100°C and 250°C	IBM-owned site, Upstate NY	450 lbs of PCE 8,100 lbs of petroleum hydrocarbons	GAC	~ $3,000,000	NA	- ISTD application for treatment of PCE and fuel oil
In Situ Thermal Desorption (ISTD) combined with Steam Enhanced Extraction (SEE) at an Active Manufacturing Facility in Florida	TerraTherm	2013	Case Study	TerraTherm	Field	Implementation	Combined technique: thermal desorption & steam enhanced	CVOCs	Sand, clay, interbedded	41 feet	NA	100°C	Active Manufacturing Facility in Florida	4,000 lbs in vapor phase and 700 lbs in liquid phase	FTIR for continuous monitoring of air discharge	NA	NA	- ISTD application for treatment of TCE, DCE, VC, and 1,4-dioxane
In Situ Thermal Remediation of Contaminants Within a Former Wood Treatment Area	TerraTherm	2006	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	PAHs, PCP & dioxins	Silty	90 feet	NA	300°C	Former wood treatment facility in Alhambra, California	All remedial goals met	Thermal oxidizer, heat exchanger, and GAC for offgas	NA	NA	- ISTD application for treatment of PAHs, PCPs, and dioxins
ISTD and SEE Case Study: Arnold Air Force Base, TN	TerraTherm	2009	Case Study	TerraTherm	Field	Implementation	Combined technique: ISTD & SEE	PCE	Clay	90 feet	NA	NA	Arnold Air Force Base, TN	165,000 lbs of VOCs removed	NA	NA	NA	- ISTD and SEE for treatment of PCE
ISTD Beneath Active Dry-Cleaning Facility; Knullen, Odense, Denmark	TerraTherm	2008	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	PCE	Fill, clay, and sandy	46 feet	NA	100°C	Active Dry-Cleaning Facility; Knullen, Odense, Denmark	7,700 lbs of PCE recovered; 95-99.75% removal efficiency	NA	NA	NA	- ISTD and SEE for treatment of PCE
ISTD of Three Separate Treatment Areas at a Brownfield Site: Midler Avenue, Syracuse, NY	TerraTherm	2007	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	PCE	Fill over peat & marl overlying clay	30 feet	NA	100°C	Brownfield Site: Midler Avenue, Syracuse, NY	86,000 lbs of VOCs removed	RTO for offgas	NA	NA	- ISTD implementation for treatment of 3 separate source areas

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ISTD Remediation at the Terminal One Tank Farm: San Francisco Bay, Richmond, CA	TerraTherm	2006	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	PCE	Sandy fill over bay mud	22 feet	NA	100°C	Terminal One Tank Farm: San Francisco Bay, Richmond, CA	All remedial goals met; ~ 97% contaminant reduction	GAC & ISCO with KMnO4	NA	NA	-ISTD application for removal of PCE and daughter products
NASA pilot study, Marshall Space Flight Center CVOC Site	TerraTherm	2007	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	TCE	Clay, limestone	35 feet	NA	100°C	Marshall Space Flight Center CVOC Site, Huntsville, Al	400 lbs of TCE removed	NA	NA	NA	-ISTD application for removal of TCE
Remediation of Coal Tar in a Manufactured Gas Plant Gasholder: North Adams, MA	TerraTherm	2005	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	Benzene, PAHs, coal tar	Fill & debris	18 feet	NA	325°C	Manufactured Gas Plant Gasholder: North Adams, MA	16,700 gal of coal tar and at least 300,000 lbs of contaminants removed; ~ 96-99% contaminant reduction	GAC	NA	NA	- 3-level ISTD application for removal of coal tar and DNAPL
Simultaneous CVOC Remediation in Three Treatment Areas at an Operational Manufacturing Facility: EPA Region V	TerraTherm	2004	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	TCE	Silty clay	15 feet	NA	99°C	Three Treatment Areas at an Operational Manufacturing Facility: EPA Region V, Midwest US	95% UCL < 0.2 mg/kg; no further action for soil	NA	NA	NA	- ISTD application for treatment of PCE, TCE, and TCA
TCE Remediation in Saprolite and Fractured Rock at an Active Manufacturing Facility	TerraTherm	2007	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	TCE	Fractured rock; saprolite	75 feet	NA	100°C	Active Manufacturing Facility in Southeastern US	95% UCL < 0.2 mg/kg	NA	NA	NA	- ISTD application for treatment of TCE
Teterboro Landing Brownfield Redevelopment - World's Largest In Situ Thermal Desorption Site	TerraTherm	2013	Case Study	TerraTherm	Field	Implementation	In situ thermal desorption	CVOCs	Sand, fill, silt	40 feet	NA	100°C	Teterboro, NJ	34,000 lbs of contaminants removed	NA	NA	NA	- Largest In Situ Thermal Desorption (ISTD) project to ever be completed, covering an area of 3.2 acres (1.3 hectares)
Thermally Enhanced Soil Vapor Extraction to Simultaneously Treat Eight Separate Source Areas: Dunn Field, Defense Depot (DLA), Memphis, TN	TerraTherm	2008	Case Study	TerraTherm	Field	Implementation	ISTD, Thermally-enhanced SVE	CVOCs	Silty clay and loess	30 feet	NA	90-100°C	Dunn Field, Defense Depot, Memphis, TN	12,500 lbs of contaminants removed from soil	ZVI, ZVI PRB, and MNA for GW	NA	NA	- Thermally enhanced SVE
Thermally Enhanced SVE to Remediate CVOCs at a Former Manufacturing Facility: Southern California Technology Demonstration	TerraTherm	2005	Case Study	TerraTherm	Field	Implementation	Thermally-enhanced SVE	1,2-DCA	Silty clay over sand	40 feet	NA	100°C	Former Manufacturing Facility, Southern CA	99.9% reduction in soil, 99% reduction in GW	NA	NA	NA	- Thermally enhanced SVE
In Situ Thermal Treatment of Chlorinated Solvent Source Zones	Kingston, J. L. T., P. C. Johnson, B. H. Kueper, et al.	2014	Book chapter	Chlorinated Solvent Source Zone Remediation	Literature review	State of the practice	ISTR											
DNAPL Removal Action: Alameda Navy Base, Alameda, CA	TRS	2007	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Fill and fine grain soil	36 feet	NA	NA	Alameda Navy Base, Alameda, California	98% reduction in contaminant concentrations in GW	Vapor GAC	NA	NA	- ERH application for treatment of DNAPL source consisting of chlorinated ethenes and ethanes
Remediation of TCE in Soil and Groundwater to 95 Feet Below Grade: Pemaco Superfund Site, Maywood, CA	TRS	2008	Case Study	TRS	Field	Implementation	ERH	TCE	Interbedded clay, silt, and sand with a complex series of stacked aquifers and perched water zones	95 feet	NA	NA	Pemaco Superfund Site, Maywood, CA	99.65% reduction in GW contaminant concentrations	FTO & GAC	NA	NA	- ERH application to remove as much TCE mass in GW as possible
World's Deepest DNAPL Remediation Confidential Site, Los Angeles, California	TRS	2008	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents and BTEX	Primarily sand	130 feet	NA	NA	Former electronics manufacturing facility, Los Angeles, CA	> 33,000 lbs of NAPL recovered; 99.7% reduction of cVOCs in soil	NA	NA	NA	- ERH application to recover as much NAPL mass as possible
Former Dry Cleaner Source Area Remediation of PCE in Soil and Groundwater: El Centro, CA	TRS	2007	Case Study	TRS	Field	Implementation	ERH	PCE	Clay and silt	32 feet	NA	NA	Former Dry Cleaner, El Centro, CA	99.99% and 99.5% reduction in soil and groundwater, respectively	NA	NA	NA	- ERH application to remove PCE in soil and GW
Groundwater Remediation of TCE and Freon 113 in the Presence of Operating, Buried Utilities: No Further Action following 3.5 Years of MNA	TRS	2010	Case Study	TRS	Field	Implementation	ERH	TCE and Freon 113	Sand, gravel, clay, and silt	45 feet	NA	NA	Confidential site, Goleta, CA	98% reduction for TCE and 99% for Freon 113	MNA	NA	NA	- ERH application for removal of TCE and Freon 113 followed by MNA - > 2 orders of magnitude reduction of TCE 3.5 years following ERH --> no further action
Standard Fixed Price Remediation of Stoddard Solvents at a Former Army Base Dry Cleaner – The Presidio, San Francisco, California	TRS	2012	Case Study	TRS	Field	Implementation	ERH	TPH	Silt clay, bay mud with intermittent sand seams	12 feet	NA	NA	Former Army Base Dry Cleaner – The Presidio, San Francisco, California	99.9% reduction on average	Oxidizer	NA	NA	- ERH application for treatment of TPH - Soil cleanup goals were not met in two small areas at the site due to interferences from heavy-end hydrocarbons and the presence of plastic sheeting that limited the effectiveness of the VR system
Guaranteed PCE and TCE Remediation at Hazardous Waste Facility Confidential Client – Newark, CA	TRS	2012	Case Study	TRS	Field	Implementation	ERH	PCE, TCE	Fill, silty clay with sandy, gravelly lenses	25 feet	NA	NA	Confidential site, Newark, CA	99.99% reduction in PCE and TCE soil concentrations	GAC	NA	NA	- ERH application for treatment of chlorinated solvents and other VOCs
Hydrolysis Remediation of TCA and TCE in Soil and Groundwater	TRS	2013	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Sand, clay and clay lenses, silt and gravel in 2 zones divided by a silt/clay aquitard	30 feet	NA	NA	Industrial site in San Diego, CA	> 99.9% reduction in soil and GW contaminant concentrations	Steam regenerated GAC	NA	NA	- ERH application for treatment of chlorinated VOCs by physical means or hydrolysis
ERH & MPE Remediation of DNAPL and LNAPL: Fort Lewis Superfund Site, Washington	TRS	2007	Case Study	TRS	Field	Implementation	ERH	TPH & chlorinated solvents	Sand, gravel, clay, and silt	35 feet	NA	NA	Fort Lewis Superfund Site, Washington	> 99% reduction in soil and groundwater contaminant concentration	FTO with acid scrubber	NA	NA	- Application of ERH and MPE for treatment of chlorinated solvents and petroleum, oil, and lubricants
Full Scale Remediation of PCE, TCE and TetCA using ERH at Fort Richardson, Anchorage, AK	TRS	2005	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Clay and silt	40 feet	NA	100°C	Fort Richardson, Anchorage, AK	97% and 99% reduction in groundwater and soil, respectively	Air stripping, SVE, oxidizer	NA	NA	- ERH application for DNAPL recovery in tight, saturated soil
Heat-Enhanced Chemical Oxidation Using ERH for Remediation of PCP in Soil and Groundwater	TRS	2010	Case Study	TRS	Field	Implementation	ERH	PCP	Silty sand	22 feet	NA	50°C	Former bulk oil terminal, Seattle, WA	98.6% reduction	Persulfate injections	NA	NA	- Combined technique involving ERH and ISCO for oxidation of PCP
Deep DNAPL remediation: Portland, OR	TRS	1999	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Silt and sand	60 feet	NA	NA	Commercial site, Portland, OR	99% reduction	GAC	NA	NA	- ERH application for treatment of TCE DNAPL
Guaranteed Remediation of TCE and PCE Under an Active Chemical Distribution Facility– Seattle, WA	TRS	2014	Case Study	TRS	Field	Implementation	ERH	PCE and TCE	Sand, clay, silt, and silty sand	65 feet	NA	NA	Former chemical plant, Seattle, WA	82-99% reduction in GW		NA	NA	
ERH Enhanced Bioremediation: Fort Wainwright, Alaska	TRS	2014	Case Study	TRS	Field	Implementation	ERH	Hydrocarbons	Gravelly sand	18 feet	NA	15 to 30°C	West Quartermaster's Fueling System, Fort Wainwright near Fairbanks, Alaska	NA	NA	NA	NA	- Pilot study utilizing ERH and radio-frequency heating to aid bioremediation of hydrocarbons - ERH was found to be more cost effective than radio-frequency heating
Combined Remedies for Improved DNAPL Cleanup Performance: Well 12A Superfund Site, Tacoma, WA	TRS	2014	Case Study	TRS	Field	Implementation	ERH	TCE	Sand, gravel, clay, and silt	55 feet	NA	NA	Well 12A Superfund Site, Tacoma, WA	99.9% reduction in soil contaminant concentration	Bioremediation in downgradient plume	NA	NA	- Low-temperature thermally-enhanced bio pilot study in progress

Appendix A. Thermal Treatment Literature Database

Title	Author	Year of Publication	Type of Publication	Source of Publication	Type of Study	Study objective	Thermal Technology	Contaminants of Concern	Lithology	Max Treatment Depth	Energy Sources	Target/achievable temperature	Site	Contamination Removal	Additional Removal Activities	Total project cost	Treatment unit cost ($/cy)	Brief Summary/Noteworthy findings
Rapid ERH Remediation for Brownfield Redevelopment Saves Client $10M	TRS	2014	Case Study	TRS	Field	Implementation	ERH	PCE	Sand, silt and clay with some gravels	40 feet	NA	NA	Former commercial laundry and dry cleaning, South Lake Union, Seattle, WA	98% reduction in PCE soil and GW concentration	Bioremediation follow-up	NA	NA	- ERH application for treatment of PCE - Bioremediation used as follow-up polishing treatment
Source Area Remediation of TCE under a Storm Water Retention Basin, Everett, Washington	TRS	2015	Case Study	TRS	Field	Implementation	ERH	TCE	Sand and silt	60 feet	NA	NA	Powder Mill Gulch storm water retention basin, Everett, WA	94% reduction, on average	NA	NA	NA	- Unique ERH application under water, beneath an operating 4-acre stormwater detention basin
Source Area Remediation of PCE in Soil: Fair Lawn, New Jersey	TRS	2008	Case Study	TRS	Field	Implementation	ERH	PCE	Glacial till overlying fractured sandstone bedrock	20 feet	NA	NA	Former Topps Dry Cleaners property, Fair Lawn, NJ	99.9% and 98% reduction in soil and GW, respectively	NA	NA	NA	- ERH application partly in fractured bedrock
Full Scale Remediation of Trichloroethene and Benzene, Toluene, Ethyl Benzene, Xylene (BTEX) in Soil Using Six Phase Soil Heating - Niagara Falls, NY	TRS	2009	Case Study	TRS	Field	Implementation	ERH	TCE	Glacial till overlying fractured bedrock	10 feet	NA	NA	Niagara Falls International Airport Air Reserve Station, Niagara Falls, New York	68% TCE reduction	NA	NA	NA	- ERH application partly in fractured bedrock
Guaranteed Performance Based Remediation of Tetrachloroethene, Queens, New York	TRS	2009	Case Study	TRS	Field	Implementation	ERH	PCE	Sand	55 feet	NA	NA	Westside Corporation site in Queens, New York	99.9996% reduction, on average	Catalytic oxidizer	NA	NA	- ERH application for treatment of PCE
Guaranteed Remediation of TCE, TCA and Freon 113 Confidential Client – Upstate New York	TRS	2015	Case Study	TRS	Field	Implementation	ERH	TCE, TCA, and Freon 113	Sand, clay, gravel, till, shale bedrock	26 feet	NA	NA	Former storage yard in south central New York	99.99% reduction for all COCs	GAC	NA	NA	- Treatment extends 5' into the shale bedrock
Guaranteed Remediation of TCE DNAPL Confidential Client – Queens, NY	TRS	2012	Case Study	TRS	Field	Implementation	ERH	TCE	Sand	42 feet	NA	NA	Mixed commercial and residential area, Queens, NY	99.8% reduction in GW TCE	GAC	NA	NA	- ERH application for TCE treatment
Guaranteed remediation of Benzene in soil & groundwater Southern New Jersey	TRS	2014	Case Study	TRS	Field	Implementation	ERH	Benzene	Sand, silt, and gravel	37 feet	NA	NA	Former gas station, NJ	> 99% benzene reduction in soil and groundwater	NA	NA	NA	- ERH application for treatment of benzene
TCE Remediation at an Operating Railroad Fueling Facility: Glendive, Montana	TRS	2007	Case Study	TRS	Field	Implementation	ERH	TCE	Silty and clayey sandl stiff clay	22 feet	NA	NA	Active railroad fueling facility in Glendive, Montana	99.5% TCE reduction in soil	NA	NA	NA	- ERH application for TCE treatment
Remediation of TCE DNAPL under an Operating Industrial Manufacturing Facility - Air Force Plant 4, Fort Worth, TX	TRS	2002	Case Study	TRS	Field	Implementation	ERH	TCE	Sand, gravel, clay, silt, and weathered limestone bedrock	37 feet	NA	NA	Air Force Plant 4 in Fort Worth, TX	90% TCE reduction in soil and GW	NA	NA	NA	- ERH application for TCE treatment - Angled drilling employed
Remediation of TCE NAPL in Active Alleyway, Arlington, Texas	TRS	2012	Case Study	TRS	Field	Implementation	ERH	TCE and Freon 113	Clay and silty clay overlying shale	32.5 feet	NA	NA	Narrow alleyway between buildings in Arlington, TX	95.5 and 99.9% reduction in TCE and Freon 113, respectively	GAC	NA	NA	- ERH application extends into weathered shale bedrock
Remediation of Trichloroethene using Electrical Resistance Heating at an Operating Industrial Manufacturing Facility Confidential Client, Springfield, MO	TRS	2010	Case Study	TRS	Field	Implementation	ERH	TCE	Residual clay with variable limestone and chert floaters	22 feet	NA	77°C	Operating manufacturing facility located in Springfield, Missouri	99.9% TCE reduction	NA	NA	NA	- Post-ERH DOC was 41x higher than pre-ERH value
Remediation of TCE at Former Industrial Manufacturing Facility Confidential Client – Springfield, Missouri	TRS	2012	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Residual clay with variable limestone and chert floaters and limestone pinnacles	65 feet	NA	NA	Former industrial manufacturing facility, Springfield, MO	> 99% reduction in soil contaminant concentration	NA	NA	NA	- ERH application extends into shale bedrock - Foam insulation used to improve vapor and steam recovery, heat retention, and protection from the elements
Removing CVOCs Under a Building Equals Increased Property Value, Tucker, Georgia	TRS	NA	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Weathered bedrock	19 feet	NA	NA	Manufacturing building, Tucker, GA	99.98% reduction in cVOCs	GAC	NA	NA	- ERH application for treatment of cVOCs in weathered bedrock
ERH and Multiphase Extraction for Remediation of LNAPL Under a Building	TRS	1999	Case Study	TRS	Field	Implementation	ERH & MPE	Kerosene-like specialty fuel	Sandy clay saprolite	27 feet	NA	NA	Manufacturing facility, southeastern US	Remove 10 feet of free product to 1/8"	NA	NA	NA	- ERH application to aid recovery of hydrocarbon free product
Guaranteed Performance Based/Fixed Price Remediation of PCE DNAPL, U.S. Navy Base Charleston, SC	TRS	2010	Case Study	TRS	Field	Implementation	ERH	PCE	Silty sand with a thin clay layer	11 feet	NA	NA	Navy Base in Charleston, South Carolina	95% PCE reduction in GW	NA	NA	NA	- ERH application for treatment of PCE DNAPL
U.S. DOE Paducah Gaseous Diffusion Plant in Kevil, Kentucky Remediation of TCE DNAPL using ERH at 100 Feet Below Ground Surface	TRS	2003	Case Study	TRS	Field	Implementation	ERH	TCE	Silt, clay, gravel, and sand	97 feet	NA	NA	U.S. DOE Paducah Gaseous Diffusion Plant, Kevil, Kentucky	99% reduction	GAC	NA	NA	- ERH application for TCE treatment
Full Scale Remediation of Volatile and Semi-Volatile Organic Compounds using Electrical Resistance Heating, Washington, NC	TRS	2006	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Silt and clay	14 feet	NA	87°C	Hamilton Beach Proctor Silex Facility, Washington, North Carolina	80% and 95% reduction in soil and GW, respectively	NA	NA	NA	- ERH application for treatment of SVOCs
Remediation of Methylene Chloride in Soil and Groundwater beneath former Manufacturing Facility, Northwest Atlanta, GA	TRS	2015	Case Study	TRS	Field	Implementation	ERH	TCE and methylene chloride	Saprolite clay	70 feet	NA	NA	Industrial adhesive manufacturing facility, Atlanta, GA	> 99.9% reduction in soil and GW	GAC	NA	NA	- ERH application for TCE and methylene chloride
VOC Remediation Under an Active Manufacturing Facility Lockheed Martin Airforce Plant 6 - Marietta, GA	TRS	2012	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Silty clay with fine to medium sand	20 feet	NA	NA	Lockheed Martin Aeronautics manufacturing facility in Marietta, Georgia	98.5% reduction in total VOCs	GAC	NA	NA	- ERH application for treatment of cVOCs
Demonstration of ERH Remediation for TCE DNAPL: Cape Canaveral, Florida	TRS	2000	Case Study	TRS	Field	Implementation	ERH	TCE	Fine sand with shells	46 feet	NA	NA	Engineering Services Building at Launch Complex 34 in Cape Canaveral, Florida	90% TCE reduction in soil	NA	NA	NA	- ERH application for treatment of TCE
ERH in Soil and Groundwater U.S. Army - Redstone Arsenal Alabama	TRS	2015	Case Study	TRS	Field	Implementation	ERH	TCE	Silt and clay overburden with Karst limestone bedrock	68 feet	NA	NA	Redstone Arsenal, Huntsville, Alabama	> 90% reduction in soil and GW	GAC	NA	NA	- ERH application for treatment of TCE
TCE Remediation at Former Manufacturing Facility Confidential Client - Batavia, IL	TRS	2010	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Silty clay	20 feet	NA	NA	Former manufacturing facility in Batavia, IL	99.5% reduction in total cVOCs	NA	NA	NA	- ERH application for treatment of chlorinated solvents
Guaranteed Fixed Price Remediation of PCE and TCE in Soil Confidential Client, Chicago, IL	TRS	2006	Case Study	TRS	Field	Implementation	ERH	PCE and TCE	Silty sand overlying clay	20.3 feet	NA	NA	Lab/manufacturing facility in Chicago, IL	80% and 87% reduction in TCE and PCE in soil, respectively	GAC	NA	NA	- First use of sheet pile electrodes
ERH Remediation of Methylene Chloride in the Vadose Zone	TRS	2000	Case Study	TRS	Field	Implementation	ERH	Methylene chloride	Glacial till and silty clay	20 feet	NA	NA	Waukegan, Illinois	99.8% reduction in soil	NA	NA	NA	- ERH application for treatment of methylene chloride
ERH Remediation of TCE DNAPL Underneath a Large Warehouse	TRS	1999	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Silty sands with clay lenses	24 feet	NA	NA	Former manufacturing facility, Skokie, Illinois	99% reduction in GW	NA	NA	NA	- ERH application for treatment of TCE - No further action issued in 2000
Guaranteed Fixed Price Remediation of TCE, PCE and VC in Soil and Bedrock under an Active Manufacturing Facility Confidential Client: Greensburg, IN	TRS	2009	Case Study	TRS	Field	Implementation	ERH	Chlorinated solvents	Clay and sand overlying dolomite bedrock	28 feet	NA	NA	Active manufacturing facility, Greensburg, IN	< 95% UCL values	GAC	NA	NA	- ERH application extending into bedrock
Source Area Remediation of TCE in Soil and Groundwater Fort Wayne, Indiana	TRS	2005	Case Study	TRS	Field	Implementation	ERH	TCE	Muddy glacial till with heaving sands and bowling ball sized rocks	34 feet	NA	NA	Abandoned steel manufacturing building, Fort Wayne, Indiana	93.4% TCE mass reduction	NA	NA	NA	- ERH application for treatment of TCE

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TCE Remediation in Low Permeability Soil, Olney, Illinois	TRS	2009	Case Study	TRS	Field	Implementation	ERH	TCE	Low permeability clay and silt	35 feet	NA	NA	Confidential site, Olney, Illinois	99.9999% TCE reduction in soil	NA	NA	NA	- ERH application for treatment of TCE
Guaranteed Fixed Price PCE Remediation – Site 22 Naval Station, Great Lakes, Illinois	TRS	2006	Case Study	TRS	Field	Implementation	ERH	PCE	Gravel, silty-clay & cinders – vadose zone; clay, silt, sand & gravel – saturated zone	17 feet	NA	NA	Old dry cleaning facility, Great Lakes, Illinois	95.5% PCE reduction in soil	GAC	NA	NA	- ERH application for treatment of PCE
Guaranteed Performance Based Full Scale Remediation of PCE using ERH under an Operating Shopping Mall, Chicago, IL	TRS	2003	Case Study	TRS	Field	Implementation	ERH	PCE	Clay and silt	23 feet	NA	NA	Operating Shopping Mall, Chicago, IL	99% reduction in soil	NA	NA	NA	- ERH application for treatment of PCE
Guaranteed Fixed Price Remediation of Benzene in Soil and Groundwater on a Busy Intersection, Bedford, Ohio	TRS	2006	Case Study	TRS	Field	Implementation	ERH	Benzene	Clay	24 feet	NA	NA	Busy street within a commercial/ residential area, Bedford, Ohio	98% reduction	Catalytic oxidizer	NA	NA	- ERH application for treatment of benzene
Remediation of PCE Belowgrade in an Active Alley Southside Chicago, IL	TRS	2007	Case Study	TRS	Field	Implementation	ERH	PCE	Gravel, clay, silt, sand with bedrock	31 feet	NA	NA	Dry cleaner facility in an active alley behind a shopping mall, Chicago, IL	99.996% reduction in soil	NA	NA	NA	- ERH application extending into bedrock
PCE Remediation Under a Building, Chicago, Illinois	TRS	2010	Case Study	TRS	Field	Implementation	ERH	PCE	Clay	21 feet	NA	NA	Former electroplating facility, Chicago, Illinois	93.6% reduction	GAC	NA	NA	- ERH application for treatment of PCE
PCE Remediation at Active Manufacturing Facility Confidential Client - Adrian, MI	TRS	2010	Case Study	TRS	Field	Implementation	ERH	PCE	Clay and sand	36 feet	NA	NA	Active manufacturing facility, Adrian, MI	> 99.9% reduction in soil and GW	NA	NA	NA	- ERH application for treatment of PCE
PCE Remediation at Former Dry Cleaning Facility (Under Active Restaurant), Owosso, MI	TRS	2012	Case Study	TRS	Field	Implementation	ERH	PCE	Silty sand, clayey silt to silty clay	15 feet	NA	~ 90°C	Former Dry Cleaning Facility, Owosso, IL	All contract goals were met	GAC	NA	NA	- ERH application for treatment of PCE
Remediation of Chlorinated Volatile Organic Compounds in Soil and Groundwater Adjacent to an Occupied Building using ERH with Sheet Pile Electrodes, Indianapolis, IN	TRS	2012	Case Study	TRS	Field	Implementation	ERH	TCE and VC	Sand and clay	44 feet	NA	~ 120°C	Former warehouse and manufacturing facility, Indianapolis, IN	95% reduction in all cVOCs	GAC	NA	NA	- Use of sheet-piling technique for installing ERH electrodes
Guaranteed Remediation of TCE in soil, Broadview, Illinios	TRS	2014	Case Study	TRS	Field	Implementation	ERH	TCE	Fill overlying clay with some sand lenses	18 feet	NA	~ 100°C	Active vehicle maintenance facility, Broadview, IL	99.99% TCE reduction in soil	GAC	NA	NA	- ERH application for treatment of TCE
TeCA Remediation using ERH in Soil, Fractured Rock and Groundwater, U.S. Naval Station Annapolis, Maryland	TRS	NA	Case Study	TRS	Field	Implementation	ERH	TCA and TCE	Hard layer of sand, iron over fractured sandstone	70 feet	NA	NA	US Naval Academy in Annapolis, Maryland	99.9% reduction in soil	NA	NA	NA	- ERH application for treatment of TCE and TCA
Guaranteed Remediation of TCE and 1,1-DCE in soil and bedrock, Shenandoah, Virginia	TRS	2014	Case Study	TRS	Field	Implementation	ERH	TCE	Low permeability soils with limestone bedrock	37 feet	NA	NA	Active parts manufacturing facility, Shenandoah, Virginia	> 99% reduction in soil	Thermal oxidizer and GAC	NA	NA	- ERH application for treatment of TCE and 1,1-DCE
Dry Cleaner Remediation of PCE below Operating Shopping Mall, Richmond, Virginia	TRS	2007	Case Study	TRS	Field	Implementation	ERH	PCE and TCE	Clay and silt	30 feet	NA	NA	Former dry cleaner, Richmond, Virginia	98.83% reduction	NA	NA	NA	- ERH application for treatment of PCE and TCE
TCE Remediation in Deep Bedrock, Eastern Pennsylvania	TRS	2014	Case Study	TRS	Field	Implementation	ERH	TCE and DCE	Medium to fine sand and clay (overburden from surface to 20 ft bgs). Sandstone bedrock from 20-ft to 110 ft-bgs	110 feet	NA	NA	Confidential site in eastern Pennsylvania	> 99% reduction in overburden and bedrock	NA	NA	NA	- ERH application extending into bedrock
Full Scale Remediation of Chlorinated Solvents and BTEX using ERH, Naval Weapons Industrial Reserve Plant, Bedford, Massachusetts	TRS	2003	Case Study	TRS	Field	Implementation	ERH	Benzene and cVOCs	Glacial deposits, comprised of sandy till, silty till and dense clayey till	17 feet	NA	NA	Naval Weapons Industrial Reserve Plant, Bedford, Massachusetts	> 90% contaminant reductions at all sites	NA	NA	NA	- ERH application for simultaneous remediation of chlorinated solvents and benzene at two separate locations
TCE Source Area Remediation at a Former Manufacturing Facility Confidential Client – Western Connecticut	TRS	2012	Case Study	TRS	Field	Implementation	ERH	TCE	Urban Fill underlain by glacial till, weathered bedrock, and competent bedrock	45 feet	NA	NA	Former metals processing and manufacturing facility, Western CT	95.9% reduction	Thermal oxidizer	NA	NA	- ERH application for treatment of TCE